ISOTOPES AND RADIATION TECHNOLOGY

A Quarterly Technical Progress Review

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ISOTOPES INFORMATION CENTER

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Isotopes and Radiation Technology

is a Technical Progress Review prepared by the Isotopes Information Center, Oak Ridge National Laboratory, at the request of the Divisions of Technical Information and Isotopes Development, U. S. Atomic Energy Commission. This Review is intended to assist those interested in keeping abreast of significant developments in the fields of isotopes and radiation technology. It is not a comprehensive review of all literature published in this field during a given quarter; rather, it is a mechanism for presenting concise, selected reviews of information on subjects of prevailing Commission interest as it becomes available.

This Review attempts to relate the published results of research and development sponsored by the Division of Isotopes Development to significant developments in radioisotopes and radiation technology, as reported in the world literature. Coverage includes isotope production and development, isotope technology development, isotope applications technology, process radiation development, and radiation processing of food and medical supplies.

In addition to reviews of current literature and special review articles dealing with specific isotopes, facilities, and applications, this publication occasionally contains feature articles prepared by recognized experts on specific topics of current interest. Critical evaluations and interpretations presented are those of the editors and invited reviewers; therefore readers are encouraged to consult the original references in order to obtain all the background of the work reported and the interpretation of the results given by the original authors.

The subject headings listed below have been adopted to help maintain continuity and order, from one issue to the next, in the material reviewed. All reviews, except Feature Articles, will be arranged under these headings; but any one issue will not necessarily contain all the headings.

Isotope Production and Development
Isotope Technology Development
Food Irradiation
Process Radiation Development
Source Development
Isotopic Heat and Power Development
Applications in Life Sciences
Safety
Isotopes Around the World
Miscellaneous

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The United States Atomic Energy Commission publishes the Technical Progress Reviews to meet the needs of industry and government for concise summaries of current nuclear developments. Each journal digests and evaluates the latest findings in a specific area of nuclear technology and science. *Nuclear Safety* is a bimonthly journal; the other three are quarterly journals.

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Nuclear Safety
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Reactor Materials
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Battelle Memorial Institute, Columbus Laboratories

All are available from the U. S. Government Printing Office. See the back cover for ordering instructions.

The views expressed in this publication do not necessarily represent those of the United States Atomic Energy Commission, its divisions or offices, or of any Commission advisory committee or contractor.

Availability of Reports Cited in This Review

United States Atomic Energy Commission (USAEC) reports are available at USAEC depository libraries and are sold by the Clearinghouse for Federal Scientific and Technical Information (CFSTI), National Bureau of Standards, U. S. Department of Commerce, Springfield, Va. 22151. All reports sold by CFSTI are $3.00 for printed copy and $0.65 for microfiche. Each separately bound part of a report is priced as a separate report. Some reports may not be available because of their preliminary nature; however, the information contained in them will generally be found in later progress or topical reports on the subject.

Other U. S. Government agency reports identified in this journal generally are available from CFSTI.

Private-organization reports should be requested from the originator.

United Kingdom Atomic Energy Authority (UKAEA) and Atomic Energy of Canada Limited (AECL) reports are available at USAEC depository libraries. UKAEA reports are sold by Her Majesty's Stationery Office, London; AECL reports are sold by the Scientific Document Distribution Office, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada. UKAEA and AECL reports issued after March 1, 1967, are sold by CFSTI to purchasers in the United States and its territories.

Section

I

Isotopes and Radiation Technology

Isotope Production and Development

The U. S. Radioisotope and Radiation Processing Industries—1968

(Editor's Note: The USAEC Division of Industrial Participation prepares a yearly summary of the status of the nuclear industry.[1] The section of this report dealing with the radioisotope and radiation processing industries is presented here because it provides a good summary of those industrial concerns which are active in this field. The editors thank Ernest B. Tremmel, Director of the Division of Industrial Participation, for permission to use this section and Robert J. Berte, also of the Division of Industrial Participation, for providing a copy of the manuscript prior to publication.)

Abstract: *The status of the commercial U. S. radioisotope and radiation processing industries in 1968 is reviewed, and commercial suppliers of the following types of materials and services are listed: radioisotopes, radiochemicals and radiopharmaceuticals, radioisotope sources, radiation equipment, radioisotopic power sources, and radiation processing.*

The commercial radioisotope industry in the United States continues to show a healthy growth, and 1968 has been marked by a decided increase in industrial interest in radiation processing.

Because of the many facets of industry's participation in these fields, this discussion is divided into the following sections: radiochemicals and radiopharmaceuticals, radiation-equipment suppliers (including radiographic and teletherapy units, radioisotope gages, and self-illuminating material and devices), Commission licensing actions, radioisotopic power, radiation processing, AEC Advisory Committee on Isotopes and Radiation Development, and Science Information Exchange Program.

Radiochemicals and Radiopharmaceuticals

The domestic market for radiochemicals and radiopharmaceuticals has increased during the past year by about 25% over 1967, and it is estimated that the radioisotope industry's growth will continue at this rate for the next several years.

1968 Market Prediction, 10^6 dollars	
Radiochemicals	10 to 13
Radiopharmaceuticals	12 to 15
Total	22 to 28

The estimated private sales of radiochemicals include the value of AEC-supplied radioisotopes purchased by private suppliers for further processing or repackaging and distribution.

Radioisotopes of commercial interest fall into four classes: those found in nature, such as ^{226}Ra; those deliberately produced in nuclear reactors, such as ^{60}Co and ^{14}C; those unavoidably produced in nuclear reactors through the fission process, such as ^{90}Sr and ^{137}Cs; and those produced in accelerators, such as ^{22}Na and ^{123}I. A radiochemical is a chemical compound that has been prepared by the use of a radioactive element. A radiopharmaceutical is a radiochemical that has been prepared to meet requirements for use in the human body.

We expect the market for radioisotopes will continue to expand at the rate of 25% annually as a result of new developments and increasing requirements for applications in areas such as radiation processing, medicine, and isotope-fueled power systems. Industry continues to make significant increases in its capacity to produce, process, and distribute isotopes. While the packaging and distribution of radioisotopes is performed to a great extent by private industry, the AEC is still one of the principal producers and distributors.

As in our two previous reports, we have divided the radioisotope industry into four categories: producers, processors, source fabricators, and equipment manufacturers.

Producers

A producer is defined as one who can perform target irradiation and may also perform target preparation and separation of the desired radioisotope for ultimate distribution. Radioisotopes are obtained from cyclotron bombardments, from reactor irradiations, and from separations from high-level waste streams.

Cyclotron Radioisotopes. In 1955 the AEC discontinued processing and distributing cyclotron-produced radioisotopes. Except for target preparation and irradiation services provided by Oak Ridge National Laboratory (ORNL) or by the University of Pittsburgh, the industry supplies cyclotron radioisotopes. An indication of the interest in cyclotron-produced radioisotopes may be obtained from the AEC revenue for special cyclotron irradiations listed below:

Fiscal year	Revenue, dollars
1964	126,508
1965	258,665
1966	277,713
1967	258,236
1968	163,670

Cyclotrons can generate a wide variety of radioisotopes that cannot be produced in reactors. Many have unique properties that make them especially useful or necessary for certain applications in spite of their relatively high cost. For example, the use of ^{123}I, (half-life 13 hr) instead of ^{131}I for in vivo thyroid uptake studies substantially reduces radiation exposure to patients because it emits no beta radiation. It is also very promising for brain scans and cancer research. Because of the special interest in cyclotron-produced ^{123}I by the medical profession and with the encouragement of the private processors, the Commission makes it available on a special-order basis as a processed target, similar to ^{84}Rb and ^{57}Co. Other cyclotron-produced radioisotopes of interest include ^{22}Na, ^{57}Co, ^{84}Rb, ^{11}C, ^{13}N, ^{15}O, ^{55}Fe, ^{199m}Hg, ^{49}Cr, ^{61}Cu, ^{62}Zn, and ^{73}Se.

Because of the very short half-life of the radioisotopes desired for medical applications and the difficulty in transporting usable quantities over great distances from the cyclotron, there is a need for commercial cyclotron facilities near large population centers to provide medical researchers and nuclear medicine departments with the necessary isotopes on a timely basis. Small cyclotrons, designed for medical research and isotope production, are now in use or are planned at the following locations:

Washington University Medical Center, St. Louis, Mo. (first commercially installed unit)
Massachusetts General Hospital, Boston, Mass.
Sloan-Kettering Institute, New York, N. Y.
Argonne Cancer Research Hospital, Chicago, Ill.
New England Nuclear Corporation, Boston, Mass.

The Cyclotron Corporation, Berkeley, Calif., supplied or has on order the units for the last three locations listed above, and Allis-Chalmers supplied the Washington University Medical Center and the Massachusetts General Hospital machines. Other facilities are planned in the future as the National Institutes of Health and AEC funding permits. It has been estimated that a market for some 20 such facilities may develop for medical radioisotope production by 1975.

The present market for cyclotron-produced radioisotopes is estimated at about $1.5 to $2 million per year. While the United States has been the principal supplier, cyclotron radioisotopes are also marketed by the United Kingdom, South Africa, and the USSR.

The principal industrial suppliers of cyclotron radioisotopes are:

Abbott Laboratories, North Chicago, Ill.
Cambridge Nuclear Corporation, Cambridge, Mass.
Hastings Radiochemical Works, Houston, Tex.
International Chemical and Nuclear Corporation, City of Industry, Calif.
Isotope Products Laboratory, Los Angeles, Calif.
New England Nuclear Corporation, Boston, Mass.
Nuclear Consultants Corp. (Division of Mallinckrodt Chemical Works), St. Louis, Mo.

Reactor Radioisotopes. As indicated previously, the AEC is still a principal domestic producer and distributor of radioisotopes, including those produced in reactors. However, the industry is offering an increasing number of products and higher-specific-activity material than in past years.

Commercial reactor irradiation services, for production of radioisotopes in targets supplied by customers, are offered by the following facilities: (1) General Electric Company, Pleasanton, Calif.; (2) Union Carbide Corporation, Tuxedo, N. Y.; and (3) The Babcock & Wilcox Co., Lynchburg, Va. In the future it is expected that additional private reactors, especially power reactors, will become available for large-volume radioisotope production. In a first such venture,

Neutron Products, Inc., Dickerson, Md., has been producing ^{60}Co in the Big Rock Point nuclear power reactor owned by Consumers Power Company.

Up to 1965 the Commission had withdrawn, on an ad hoc basis, from producing and distributing selected radioisotopes. In March 1965 the AEC adopted and published in the *Federal Register* formal policies and procedures for the transfer of commercial AEC radioisotope-production and -distribution activities to private industry. These policies and procedures provide for orderly AEC withdrawal from this area of activity.

Since our last report the AEC has withdrawn from production of low-specific-activity ^{60}Co, making a total of 38 reactor-produced isotopes that have been withdrawn from routine production. AEC earlier had withdrawn from furnishing high-specific-activity ^{60}Co.

Table 1 lists AEC sales of radioisotopes.

In September 1968 the AEC reduced prices for large-quantity orders of tritium and ^{210}Po. The AEC is also considering reducing its price for ^{14}C to assist in meeting price competition from foreign suppliers. The full cost of production and distribution would still be recovered for these isotopes at the reduced prices.

The AEC made available for sale limited quantities of ^{238}Pu, ^{252}Cf, ^{243}Am, and ^{244}Cm for use in private research and development. Plutonium-238 is useful for isotopic heat sources and alpha and neutron sources.

Californium-252 is the most concentrated source of neutrons known and will enable significant improvements and the miniaturization of such analytical tools as activation analysis and gaging.

Reactor-produced radioisotopes are used in a large number of applications. To name a few: medicine, agriculture, crime detection, industrial gages, and space. As stated in the introduction, the market growth is estimated to be about 25% annually for the next several years.

In the United States alone, there are currently more than 5000 doctors and medical organizations routinely using some 30 different radioisotopes in the diagnosis and treatment of many diseases. Some of the isotopes and applications include ^{60}Co as a source of radiation for treating cancer; ^{131}I for studying blood volume and cardiac diseases, locating brain tumors, diagnosing kidney and liver disorders, and, primarily, diagnosing and treating thyroid disorders (over one-half million thyroid cases annually); ^{14}C for studying metabolic diseases; ^{22}Na and ^{24}Na for measuring blood volume and diagnosing circulatory disorders; ^{68}Ga and ^{85}Sr for bone scanning; ^{99m}Tc for making radiocardiograms; ^{32}P for locating eye tumors; and ^{59}Fe for studying hemoglobin. It is estimated that between three and four million patients each year are benefiting from medical procedures using isotopes. About 98% of these procedures are diagnostic.

Foreign competition in the radioisotope market is increasing and will continue to be a problem for American firms. This is especially so in the ^{60}Co market where Canada, the United Kingdom, and Australia are major suppliers.

Table 1 AEC Sales of Radioisotopes

Fiscal year	Value, 10^6 dollars
1963	1.2
1964	1.3
1965	1.9
1966	2.3
1967	1.8
1968	1.8

Fission-Product Radioisotopes. In addition to cyclotron- and reactor-produced radioisotopes, fission-product radioisotopes are separated from high-level waste streams from AEC production facilities. The fission-product radioisotopes of principal interest are ^{90}Sr, ^{137}Cs, and ^{147}Pm. At present, fission-product isotopes are obtained from waste streams in the Richland chemical separations plant and are distributed through the Oak Ridge National Laboratory, Isotopes Sales Department. These fission products will also be available in large quantities in the future, when their production is warranted by market demands, from commercial firms operating chemical processing plants, such as Nuclear Fuel Services, Inc., Allied Chemical Company, and General Electric Company. The expanding uses of these isotopes may eventually create a source of revenue for utilities from these by-products resulting from reprocessing of fuel from reactor operation.

Fission-product radioisotopes are used in a number of industrial applications, as well as for space, power, and heat purposes. Promethium-147 and ^{90}Sr are used in radioisotope power generators. Strontium-90 is also employed in industrial thickness gages and in the treatment of certain eye disorders. Promethium-147 is also used to prepare and activate luminous sources. Cesium-137 is used as a radiation source for both industrial and medical uses.

The AEC revenue for the distribution of the above three radioisotopes is given in Table 2 for fiscal years 1965 to 1968.

Table 2 AEC Sales of ^{137}Cs, ^{147}Pm, and ^{90}Sr

	Revenue, dollars			
	1965	1966	1967	1968
^{137}Cs	192,000	27,000	60,000	83,000
^{147}Pm	28,000	12,000	55,000	56,000
^{90}Sr	3,000	65,000	59,000	188,000
Total	223,000	104,000	174,000	327,000

During the year the AEC reviewed its price schedules for the fission-product isotopes. In June 1968 the Commission announced for public comment its intention to increase the price of ^{137}Cs to recover full costs of production and distribution, and in September 1968 it decided to retain the existing price schedules of ^{90}Sr and ^{147}Pm. The Commission had reduced the prices of the above three fission-product radioisotopes in November 1965 to assist in stimulation of a market, primarily to assist the then-planned private fission-products conversion and encapsulation plant to be operated by Isochem Inc. As reported previously (1967 report), plans for this plant were canceled in early 1967.

Processors

A processor is defined as one who can prepare irradiation targets and (subsequent to irradiation in an accelerator or nuclear reactor) can separate and prepare the desired radiochemicals or radiopharmaceuticals for ultimate distribution.

A number of changes in the radioisotope industry have taken place since our last report. The following companies were involved: General Nuclear, Inc., Houston, Tex., purchased General Radioisotope Processing Company of San Ramon, Calif.; Teledyne, Inc. acquired the Nuclear Division of Martin Marietta Corporation; Cambridge Nuclear Corporation acquired Nuclear Components, Inc.; G. D. Searle & Co. formed a joint company with the UKAEA Radiochemical Centre Amersham group, known as Amersham/Searle Corp.

The principal commercial firms in this area are listed in Table 3.

Source Fabrication

There are approximately 30 commercial firms producing alpha, beta, gamma, and neutron sources. The current volume of business in radioactive sources is estimated at $2.5 to $3 million per year, significantly

Table 3 Principal Processors of Radiochemicals and Radiopharmaceuticals

	Radio-chemicals	Radio-pharmaceuticals
Abbott Laboratories, North Chicago, Ill.		X
Atomic Corporation of America, Sun Valley, Calif.	X	
Bio-Nuclear (Division of Bio-Assay Laboratories), Houston, Tex.	X	
Bio-Rad Laboratories, Richmond, Calif.	X	
Calbiochem, Los Angeles, Calif.	X	
Cambridge Nuclear Corporation, Cambridge, Mass.	X	X
General Electric Company, Pleasanton, Calif.	X	
General Nuclear, Inc., Houston, Tex.	X	
Hastings Radiochemical Works, Houston, Tex.	X	X
International Chemical & Nuclear Corp., Subsidiaries:		
ICN Chemical and Radioisotope Division, City of Industry, Calif. (includes Volk Radiochemical)	X	
Nuclear Science Division, Pittsburgh, Pa.	X	
U. S. Nuclear, Burbank, Calif.	X	
Isotopes, Inc. (a Teledyne Company), Westwood, N. J., and Baltimore, Md.	X	
New England Nuclear Corporation, Boston, Mass.	X	X
Amersham/Searle Corp. (Subsidiary of G. D. Searle & Co. and United Kingdom Atomic Energy Authority), Des Plaines, Ill.	X	X
Nuclear Consultants Corp. (Division of Mallinckrodt Chemical Works), St. Louis, Mo.	X	X
Nuclear Equipment Chemical Corp., Farmingdale, N. Y.	X	X
Schwartz Bio Research Inc. (Subsidiary of Becton, Dickinson & Co.), Orangeburg, N. Y.	X	
E. R. Squibb & Sons, New Brunswick, N. J.		X
Tracerlab (Division of Laboratory for Electronics, Inc.), Waltham, Mass.	X	
Union Carbide Corporation, Tuxedo, N. Y.	X	X

higher than our previous estimate, and is based on information furnished by several of the principal suppliers.

The principal commercial firms supplying radioactive sources are:

Atlantic Research Corp., Alexandria, Va.
Bio-Nuclear (Division of Bio-Assay Laboratories), Houston, Tex.
The Budd Company, Instruments Division, Phoenixville, Pa.
Gamma Industries, Inc., Baton Rouge, La.
General Nuclear, Inc., Houston, Tex.
Hastings Radiochemical Works, Houston, Tex.
3M Company, St. Paul, Minn.
Monsanto Research Corp., Dayton, Ohio
Nuclear-Chicago Corporation (Subsidiary of G. D. Searle & Co.), Des Plaines, Ill.
Nuclear Materials and Equipment Corp. (NUMEC), Apollo, Pa.
Picker X-Ray, Technical Operations, Inc., Burlington, Mass.
Radionics, Inc., Norristown, Pa.
Tracerlab (Division of Laboratory for Electronics, Inc.), Waltham, Mass.
U. S. Nuclear (Division of International Chemical & Nuclear Corp.), Burbank, Calif.

Equipment Manufacturers

There are six principal areas of interest in equipment: radiographic units, teletherapy units, gages, irradiators, isotopic power devices, and self-illuminating devices.

Radiographic Units

Radiographic units are manufactured by industry and not by the AEC. The commercial firms active in this field are:

The Budd Company, Instruments Division, Phoenixville, Pa.
Gamma Industries, Inc., Baton Rouge, La.
Picker X-Ray, Technical Operations, Inc., Burlington, Mass.
U. S. Nuclear (Division of International Chemical & Nuclear Corp.), Burbank, Calif.

The annual volume of sales in this field is approximately $1.5 million and is expected to continue to increase. The radioisotope units, utilizing such isotopes as ^{192}Ir, ^{60}Co, ^{137}Cs, and ^{170}Tm, compete with X-ray machines.

Teletherapy Units

There are eight commercial suppliers of teletherapy units. Four of the eight suppliers (General Electric; North American Philips Company, Inc.; Siemens America, Inc.; and Schick X-Ray Company) are distributors of foreign-made teletherapy units. The firms active in this field are:

John & W. F. Barnes Works, Automated Machine Division of The Babcock & Wilcox Co., Rockford, Ill.
General Electric Company, Milwaukee, Wis.
Tracerlab (Division of Laboratory for Electronics, Inc.), Waltham, Mass.
North American Philips Company, Inc., New York, N. Y.
Picker X-Ray Corp., Cleveland, Ohio
Schick X-Ray Company, Chicago, Ill.
Siemens America, Inc., New York, N. Y.
Westinghouse Electric Corporation, Baltimore, Md.

Since our last report the International Atomic Energy Agency has published a new directory of high-energy radiotherapy centers[2] which lists radioisotope and other high-energy teletherapy installations throughout the world. Some 1578 radiotherapy centers in 62 countries are listed with details on 2074 treatment units.

The world total of 2074 units includes 1676 ^{60}Co units and 140 ^{137}Cs units. Since 1959 the annual increase in cobalt units has been nearly constant at about 160 to 170 per year. The average new unit being installed in the United States contains 3 thousand to 4 thousand curies of high-specific-activity ^{60}Co, with some containing up to 8 thousand to 10 thousand curies. There are some 258 nonisotope teletherapy units reported, including betatrons, linear accelerators, Van de Graaff machines, and high-energy resonant transformer X-ray generators.

Radioisotope Gages

There are between 15 and 20 firms active in the radioisotope-gage field. This type of gage combines a radioisotope (alpha, beta, gamma, or neutron) source of radiation and appropriate radiation-detection elements and control equipment, which permit measurement and control of various processes. These include flow rate, thickness, level, density, and activation-analysis systems. The current market for radioisotope gages is estimated at about $25 million and is expected to grow at about 10 to 15% annually.

The principal suppliers of industrial radioisotope gages and gaging systems are:

Avionics Corporation, Succasunna, N. J.
Brun Corporation, Columbus, Ohio
Densitronics, Inc., Los Angeles, Calif.
Electronic Automation Systems Inc., Grand Island, N. Y.
The Foxboro Corporation, Foxboro, Mass.
General Nucleonics Corporation, Claremont, Calif.
Industrial Nucleonics Corporation, Columbus, Ohio
Instruments Inc., Tulsa, Okla.
Gene Lowey, Inc., Hamilton, Ohio
Ludlum Measurements, Inc., Sweetwater, Tex.
Nuclear-Chicago Corporation (subsidiary of G.D. Searle & Co.), Des Plaines, Ill.

The Ohmart Corporation, Cincinnati, Ohio
Robertshaw Controls Company, Anaheim, Calif.
Tracerlab (Division of Laboratory for Electronics, Inc.), Waltham, Mass.
Troxler Electronics Laboratories, Inc., Raleigh, N. C.

Table 4 gives sales of radioisotope gages as reported by the Bureau of the Census.

Some examples of radioisotope-gage applications include: measuring and automatically adjusting the thickness of steel sheet, paper, tire cords, textiles, plastics, and other materials; controlling sugar, fat, and meat content in food packaging; measuring soil density and moisture content; measuring snow density for water-runoff forecasting; detecting gold; and measuring the density of ocean-bottom sediments.

Table 4 Sales of Radioisotope Gages

Year	Sales, 10^6 dollars
1957	6
1958	6
1959	9
1960	10
1961	11
1962	9
1963	9.9
1964	9.7
1965	13.1
1966	14.5
1967	20*
1968	25*

*Estimated.

Self-Illuminating Materials and Devices

Beta-emitting radioisotopes, such as ^{85}Kr, tritium, and ^{147}Pm, are used in the preparation of self-illuminating materials and devices. Tritium is the most frequently used radioisotope. The growing use and interest in self-illuminating materials are reflected in the sales of tritium by the AEC given below.

Fiscal year	Kilo-curies	AEC sales, 10^3 dollars
1963	60	95
1964	112	125
1965	118	128
1966	171	196
1967	179	200
1968	179	199

The firms active in this field are:

American Atomics Corp., Tucson, Ariz.
Canrad Precision Industries, Inc., New York, N. Y.
Tracerlab (Division of Laboratory for Electronics, Inc.), Waltham, Mass.
Luminous Products Corp. (subsidiary of New England Nuclear Corp.), Boston, Mass.
3M Company, St. Paul, Minn.
Radium Chemical Co. Inc., New York, N. Y.
United States Radium Corp., Morristown, N. J.

Commission Licensing Actions in Radioisotope Area

Since our last report the AEC has taken a number of significant steps in its regulatory program and has amended, or proposed amendments of, several of its regulations concerning radioactive materials. The most important items are summarized below.

The Division of Materials Licensing issued a booklet[3] that explains in nontechnical terms the objectives of the regulatory program, how it functions, and the safety responsibilities of persons who use radioisotopes.

Effective in November 1967, Part 35 of the AEC's regulations was amended to simplify the licensing process for the medical use of radioisotopes in diagnostic procedures.

At the request of Abbott Laboratories and Jones Medical Instrument Company of Chicago, the AEC published a proposed amendment of its regulations to provide a general license to physicians, hospitals, and clinical laboratories for the use of ^{125}I and ^{131}I in tests not involving administration of radioactive material to human beings.

In response to numerous petitions received for exemption of by-product materials in self-luminous products, the Commission has revised Parts 30 and 32 in Title 10 of the *Code of Federal Regulations* (10 CFR) to exempt from control self-luminous products containing tritium, ^{85}Kr, and ^{147}Pm meeting specific safety standards and for which the end uses can reasonably be foreseen.

The AEC amended Part 33 of its regulations to provide for more flexibility to users, who have small- to intermediate-sized radioisotope programs, by establishing new types of broad licenses and expanding the scope of the uses authorized in all broad licenses.

In July 1968 the AEC adopted licensing fees, effective Oct. 1, 1968, for facilities and for certain materials licenses. Fees will be charged for licenses for by-product materials of 100,000 curies or more in

sealed sources used for irradiation of materials; for licenses for special nuclear materials in quantities sufficient to form a critical mass (except Pu–Be neutron sources), and for waste-disposal licenses specifically authorizing the receipt of waste materials from other persons for the purpose of commercial disposal by the waste-disposal licensee.

In February the AEC proposed amendment of its regulations which would redefine the basis of continued regulatory authority in agreement states over the manufacturer's transfer of products whose subsequent transfer is exempt from regulatory controls.

The AEC amended its regulations in April to increase the quantity limit of generally licensed ^{147}Pm in any single aircraft-safety device from 100 mc to 300 mc.

In June 1968 the Commission proposed an amendment to revise the present labeling requirements for generally licensed luminous aircraft-safety devices so that the label could be appropriately used on such devices within either agreement or nonagreement states.

In August 1968 the Commission proposed to exempt from licensing the use of small quantities of certain radioisotopes now under general license and to increase the number of radioisotopes, to which the exemption would apply, from 65 to 171. The proposed amendments to Part 31 are responsive to recommendations made by the Commission's Advisory Committee on Isotopes and Radiation Development and the Commission's ad hoc Radioisotopes Licensing Review Panel.

Radioisotopic Power

Publication of USAEC Report WASH-1095, "Radioisotopes—Production and Development of Large-Scale Uses" (which was referenced in *The Nuclear Industry—1967*) was delayed until May 1968 (Ref. 4). This report reviews AEC's current programs and future plans for the development of large-scale uses of radioisotopes in electric power, thermal energy, and process radiation applications.

The heat released when isotopes decay is now beginning to be used on a large scale for generating the power required in various specialized applications. The growth of isotopic power applications has been limited by the lack of availability of several of the isotopes which, in turn, affects the demands of potential large-scale users such as the Department of Defense and the National Aeronautics and Space Administration. Also, space and military requirements for isotope-powered systems have not developed as fast as expected. Detailed forecasts of requirements for ^{238}Pu; for the intermediate-half-life isotopes ^{90}Sr and ^{137}Cs; and for short-lived isotopes such as ^{60}Co, ^{210}Po, ^{170}Tm, and ^{147}Pm are given in WASH-1095, referenced above, for various applications.

It is expected that the expanding nuclear power economy should contribute significantly to the production of isotopes such as ^{238}Pu, ^{244}Cm, and ^{90}Sr as a by-product of reactor operation and chemical reprocessing operations. As mentioned previously, some isotopes, e.g., ^{60}Co and ^{170}Tm, may be produced in power reactors through the irradiation of target materials.

Radioisotope power applications fall into the following general categories:

1. Space electric-power applications include weather, communications, and navigation satellites; space exploratory power systems, such as that for the Apollo Lunar Surface Experiment; and space mission requirements.

2. Terrestrial power applications include remote weather stations, navigation buoys and beacons, offshore oil rigs, cardiac pacemakers, and undersea power systems.

3. Thermal applications include spacecraft and swimsuit heaters, waste-water reprocessing systems for manned space missions, and energy sources for heart pumps and small undersea propulsion systems.

4. Isotopic propulsion systems are used for auxiliary spacecraft propulsion.

The federal government is the principal market for these devices at the present time. While forecasts of isotope requirements are given in WASH-1095, the dollar value of power-producing devices cannot really be estimated yet. Substantial commercial markets for applications, such as direct-broadcast satellites and marine and remote-land power systems, could develop eventually. The cardiac pacemaker and the artificial heart appear to be among the most promising future markets. It is estimated that there could be a need for about 10,000 cardiac pacemakers per year in the future. These units produce 150 to 200 $\mu w(e)$ of power and do not require large quantitites of ^{238}Pu. The need for artificial-heart-implantation operations has been estimated to be as high as 100,000 or more per year. At that rate all foreseen supplies of ^{238}Pu could be required for these hearts if their implantation is eventually successfully developed.

The following companies are active in the isotopic power-generation field:

Aerojet-General Corporation, San Ramon, Calif.
Atomics International, Canoga Park, Calif.
Douglas Laboratories, Richland, Wash.
3M Company, St. Paul, Minn.
Nuclear Materials and Equipment Corp. (NUMEC), Apollo, Pa.
Sanders Nuclear Corporation, Nashua, N. H.
Isotopes, Inc. (a Teledyne Company), Westwood, N. J., and Baltimore, Md.
TRW Systems, Redondo Beach, Calif.
Hittman Associates Corp., Columbia, Md.
Thermo Electron Corp., Waltham, Mass.
Westinghouse Electric Corp., Pittsburgh, Pa.

It is expected that other firms will enter this field as the market develops. Significant activities by commercial firms are described below.

NUMEC has shipped one 50-mw generator for Navy testing and has sold two 2.5-watt units to a foreign customer.

Martin Marietta Corporation sold its nuclear activities to Teledyne, whose subsidiary, Isotopes, Inc., will take over the Martin contracts and programs. Martin Marietta now has supplied 10 units, 9 of which are still operating. Georgia Institute of Technology, the Navy, and Sinclair Oil are the principal users. A new company, formed by Martin Marietta, Offshore Systems, Inc., plans to market an underwater-wellhead control system powered by two 3-watt radioisotope generators and a blowout-preventer system for underwater wells, also powered by a radioisotope generator.

The Radiation Processing Industry

During the year the AEC's Division of Isotopes Development completed a study of radiation processing applicable to chemical systems. This study was conducted to determine the status of industrial interest and investment in radiation processing, to determine the present attitude of industrial companies regarding radiation processing, and to assess the AEC's programs of research and development in radiation processing.[5]

While the study has been reviewed in at least one trade journal, a number of the more significant observations and statistics resulting from this study are presented in this section.

The radiation processing market has been estimated, in terms of the value of sales of products processed, at about $100 million in 1967. Industrial radiation processing could possibly grow at a rate of 50% annually for the next 2 years and is expected to grow at 25% annually.

AEC has spent some $8 million on radiation processing research and development and industry, an estimated $50 to $75 million over the past 20 years. The current annual level of support by AEC is $1.4 million and by industry, $10 to $15 million.

The radiation processing field is divided into machine- or accelerator-produced radiation and isotope radiation, each of which possesses some advantages and disadvantages over the other. For example, machines can be operated at variable energy-output levels to accommodate the work to be processed and can be turned off. Isotope radiation cannot be turned off but is suitable for bulk processing of chemicals and products requiring great penetration where machine radiation is inadequate. In applications where a low dose rate is a factor, such as the polymerization of a monomer in a fibrous substance (i.e., wood–plastics), isotopes are more suitable. At the present time, of the total energy output from radiation sources in irradiation facilities, 90% is delivered by machines.

The most promising radiation processing applications in use or under development are listed below.

Curing of surface coatings by machine irradiation of special lacquers and paints. The Boise Cascade Corp. (using the Electrocure process under license to the Ford Motor Company) and Radiation Dynamics, Inc. (the Dynacote process) are the principal firms. PPG Industries and others are also doing development work in this area.

Irradiation of wood–plastic combinations to produce superior qualities in strength, appearance, and surface properties has been under way for some time by American Novawood Corporation and Lockheed-Georgia Company. Atlantic Richfield Co., Gamma Process Company, and Radiation Machinery Corporation have recently entered this field. All of the above firms use ^{60}Co.

Crosslinking of polyethylene films to produce special wire coatings, insulating materials, heat shrinkable packaging film, and bags of improved physical properties. The major companies in this area are Raychem Corp., W. R. Grace & Co. (Cryovac Division), High Energy Processing Corporation, the Electronized Chemicals Corp. (subsidiary of High Voltage Engineering Corp.), and International Telephone and Telegraph Corporation's Wire and Cable Division.

Preparation of specialty copolymers for use as battery separators for Department of Defense requirements. Radiation Applications, Inc., and High Energy Processing Corporation are active in this area.

Table 5 Irradiators Supporting the Food-Irradiation Effort

Irradiator	Description	Location	Purpose
		Research	
Research	30,000 to 40,000 curies of ^{60}Co, pool type	Massachusetts Institute of Technology University of California (Davis) University of Washington University of Florida	On-site research
On-Ship No. 3	36,000 curies of ^{60}Co, 18-ton portable unit	University of Nebraska	On-site research
Portable Cesium No. 1	170,000 curies of ^{137}Cs, 18-ton portable unit	Operated for AEC by Isotopes, Inc., Westwood, N. J.	Demonstration to and use by industry
		Pilot Plant	
Marine Products Development Irradiator (MPDI)	250,000 curies of ^{60}Co, 1000 lb/hr at pasteurizing dose	Gloucester, Mass.	Seafood irradiation
Mobile Gamma Irradiator (MGI)	100,000 curies of ^{60}Co, 1000 lb/hr at pasteurizing dose	Davis, Calif.	Fruit irradiation
Grain Products Irradiator (GPI)	25,000 curies of ^{60}Co, 5000 lb/hr bulk or 2800 lb/hr packaged	Savannah, Ga.	Grain-products disinfestation
Hawaii Development Irradiator (HDI)	225,000 curies of ^{60}Co, 4000 lb/hr at pasteurizing dose	Honolulu, Hawaii	Tropical fruits

Synthesis of new graft copolymer fibers with improved "crease resistance" and "soil resistance" properties by Deering Milliken & Co., Inc.

Synthesis of ethyl bromide by Dow Chemical Co.

The controlled degradation of polyox, a polyethylene oxide polymer, by Union Carbide Corporation.

Irradiation Processing of Foods

Irradiation processing of foods attracted a great amount of attention this year as a result of the Food and Drug Administration's (FDA) refusal to approve ham and its withdrawal of approval of bacon. Both products are in the Army Program, and the petitions were submitted by the Army. This action delayed the food programs of the Army, the AEC, and commercial firms for at least the 4- to 5-year period required to conduct new animal-feeding tests.

At present, wheat and wheat products and white potatoes have been cleared by FDA for irradiation processing. A great amount of testing is under way by government agencies and private firms on additional foods such as strawberries, citrus fruits, and marine products. Other than withdrawal of bacon, there has been no change in the status of FDA approvals since our 1966 report.

The principal irradiators supporting the food-irradiation effort are listed in Table 5.

Firms Associated with Radiation Processing

In January 1968 the Business and Defense Services Administration of the Department of Commerce released a new guide to services, suppliers, and research on food irradiation.[6] The guide lists commercial firms in all areas of radiation processing, including design, engineering, and construction of facilities; design and fabrication of irradiation equipment; radiation-source suppliers; encapsulators; and electron-machine manufacturers. This year, because of the additional companies that have been identified in the above categories, we are listing firms associated with radiation processing in all categories.

Principal Firms Supplying Electron-Accelerator Equipment and/or Services or Finished Products

Company	Supply accelerators	Supply services	Supply finished product
Accelerators, Inc., Austin, Tex.	X		
Applied Radiation Corp., Walnut Creek, Calif.	X	X	
Boise Cascade Corp., Boise, Idaho		X	X
Columbia Research Corp., Gaithersburg, Md.		X	
Electra Process Industries, Inc., Spokane, Wash.		X	
Electronized Chemicals Corp., (subsidiary of High Voltage Engineering Corp.), Burlington, Mass.		X	X
General Electric Company, Milwaukee, Wis.	X		
High Energy Processing Corporation, New Bedford, Mass.		X	X
High Voltage Engineering Corp., Burlington, Mass.	X	X	
Radiation Dynamics, Inc., Westbury, N. Y.	X	X	
Radiation Polymer (Division of Pittsburgh Plate Glass Co.), Plainfield, Ill.			X
Radiation Technology, Inc., New York, N. Y.			X
Raychem, Redwood City, Calif.			X
Raycon, Inc., South Windsor, Conn.		X	
Varian Associates, Livingston, N. J.	X	X	
Westinghouse Electric Corporation, Baltimore, Md.	X		

Commercial Radiation Processing Facilities

American Novawood Corporation, Lynchburg, Va.
American Nuclear Corp., Oak Ridge, Tenn.
Electra-Process Industries, Inc., Spokane, Wash.
Electronized Chemicals Corp., Burlington, Mass.
Gamma Process Corporation, New York, N. Y.
High Energy Processing Corporation, New Bedford, Mass.
Isotopes, Inc., Westwood, N. J.
Lockheed-Georgia Company, Dawsonville, Ga.
Neutron Products, Inc., Dickerson, Md.
Nuclear Materials and Equipment Corp. (NUMEC), Apollo, Pa.
Radiation Dynamics, Inc., Westbury, N. Y.
Radiation Machinery Corp., Parsippany, N. J.
Raycon, Inc., South Windsor, Conn.
Raychem Corp., Redwood City, Calif.
Radiation Technology, Inc., New York, N. Y.
RAI, Long Island City, N. Y.
General Electric Company, Pleasanton, Calif.

Architectural Design, Engineering, and Construction

American Novawood Corporation, Lynchburg, Va.
American Nuclear Corp., Oak Ridge, Tenn.
Atomchem Corp., Long Island, New York, N. Y.
Burns & Roe, Inc., Oradell, N. J.
Commonwealth Associates, Inc., Jackson, Mich.
A. Epstein and Sons, Inc., Chicago, Ill.
Food Industries Research & Engineering, Yakima, Wash.
Gamma Process Company, Inc., New York, N. Y.
General Electric Company, Pleasanton, Calif.
Gibbs and Hill, Inc., New York, N. Y.
Holmes & Narver, Inc., Los Angeles, Calif.
Isotopes, Inc., Westwood, N. J.
Lockheed-Georgia Company, Dawsonville, Ga.
Chas. T. Main, Inc., Boston, Mass.
Nuclear Materials and Equipment Corp. (NUMEC), Apollo, Pa.
Nuclear Technology Corp., White Plains, N. Y.
Neutron Products, Inc., Dickerson, Md.
Parsons-Jurden Corp. (subsidiary of Ralph M. Parsons Co.), New York, N. Y.
Radiation Dynamics, Inc., Westbury, N. Y.
Radiation Facilities, Inc., Lodi, N. J.
Stearns-Roger Corp., Denver, Colo.
Stone & Webster Engineering Corp., Garden City, Long Island, N. Y.
Bechtel Corp., San Francisco, Calif.
Radiation Machinery Corp., Parsippany, N. J.

Irradiation Equipment, Design and Fabrication

American Novawood Corporation, Lynchburg, Va.
American Nuclear Corporation, Oak Ridge, Tenn.
Applied Radiation Corp., Walnut Creek, Calif.
Atomchem Corp., Long Island, New York, N. Y.
Gamma Process Company, New York, N. Y.
General Electric Company, Pleasanton, Calif.
Isotopes, Inc., Westwood, N. J.
Lockheed-Georgia Company, Dawsonville, Ga.
National Lead Co., Wilmington, Del.
Nuclear Materials and Equipment Corp. (NUMEC), Apollo, Pa.
Nuclear Technology Corp., White Plains, N. Y.
Neutron Products, Inc., Dickerson, Md.
Radiation Facilities, Inc., Lodi, N. J.
Radiation Machinery Corp., Parsippany, N. J.
Stearns-Roger Corp., Denver, Colo.

Radiation Processing Source Suppliers and Encapsulators

American Nuclear Corporation, Oak Ridge, Tenn.
Atomchem Corp., Long Island, New York, N. Y.
The Babcock & Wilcox Co., Lynchburg, Va.
Gamma Process Co., New York, N. Y.
General Electric Company, Pleasanton, Calif.
Industrial Reactor Laboratory, Albinsville, N. J.
Lockheed-Georgia Company, Dawsonville, Ga.
3M Company, St. Paul, Minn.
Nuclear Materials and Equipment Corp. (NUMEC), Apollo, Pa.
Neutron Products, Inc., Dickerson, Md.
Radiation Machinery Corporation, Parsippany, N. J.

Significant Industry Changes and Announcements

Columbia Research Corporation took over operation of the 3-Mev Dynamitron electron accelerator, prevously operated by Rad-Mat Inc. in Gaithersburg, Md.

Gamma Process Company and the New York Atomic and Space Development Authority (ASDA) contracted for the construction and operation of ASDA's Malta Test Station north of Schenectady, N. Y. This will be a full-scale radiation processing facility. Gamma Process also acquired the Rose Alloy Industrial Corporation, a heavy-metals fabricator, based in Uniontown, Pa.

As noted previously, Martin Marietta sold its nuclear interest to Teledyne. The Isotopes Division of Teledyne will take over the Martin Marietta activities.

Radiation Machinery Corporation, Parsippany, N. J., was formed as a new company in the radiation processing field.

AEC Advisory Committee on Isotopes and Radiation Developments

The present AEC Advisory Committee on Isotopes and Radiation Development was established in 1958. This committee grew out of the Advisory Committee on Isotope Production and Distribution, which was formed in 1946 and terminated in 1958 when the Commission's regulatory and licensing activities were separated from the operating activities.

The Advisory Committee on Isotopes and Radiation Development reviews AEC policies and the potential development of new applications of isotopes and radiation and makes appropriate recommendations for the Commission's consideration.

The composition of this committee has been gradually changed to bring in additional representatives from various segments of the isotope industry. The present membership is given below:

Chairman: John W. Landis, Gulf General Atomic, Inc.
AEC Member: Dr. Nathaniel F. Barr, Technical Adviser to the Assistant General Manager for Research and Development
Mr. Robert E. Kettner, private consultant
Dr. Milton Burton, University of Notre Dame
Comdr. Scott Carpenter, U. S. Navy, Deep Submergence System Project
Dr. Bernard Fries, Chevron Research Company
Dr. David E. Harmer, Dow Chemical Co.
Dr. Wilfred R. Konneker, Mallinckrodt/Nuclear
Dr. James R. Maxfield, Jr., Maxfield Clinic Hospital
Dr. Donald W. Pritchard, Johns Hopkins University
Dr. Vivian T. Stannett, North Carolina State University
Dr. Paul M. Stier, Union Carbide Corporation

Science Information Exchange (SIE) Program

A cooperative model program, to register private research and development in isotopes and radiation, was initiated by the AEC and the Science Information Exchange of the Smithsonian Institution in April 1967.

This model program with isotopes has been completed and is regarded as moderately successful. This type of program is mutually beneficial to industry and government, in that the SIE system registers and catalogs research work at the time it is initiated, rather than after it appears in reports and journals. The reporting system, which is entirely voluntary, is expected to be useful and informative without, at the same time, revealing proprietary information concerning work in specific companies. The purpose of this SIE program is to develop an overall isotope and radiation program, with a minimum of overlapping between private-industry-sponsored and government-sponsored work.

The SIE registers over 95,000 basic and applied research projects annually from federal agencies, private foundations, universities, and private industry. SIE answers, without charge, some 50,000 questions each year from scientists, investigators, and research administrators. (RHL)

References

1. USAEC Division of Industrial Participation, *The Nuclear Industry—1968*, U. S. Government Printing Office, Washington, 1968 ($2.00).
2. P. M. Pfalzner (Comp.), *Directory of High-Energy Radiotherapy Centres*, International Atomic Energy Agency, Vienna, 1968 ($3.50).
3. USAEC Division of Materials Licensing, How To Get a License To Use Radioisotopes, U. S. Government Printing Office, Washington, 1967 ($0.30).
4. USAEC, Radioisotopes—Production and Development of Large-Scale Uses, U. S. Government Printing Office, Washington, 1968 ($0.50). This report was also published in two parts in *Isotopes and Radiation Technology*, 6(2): 131-144 (Winter 1968–1969) and 6(3): 238-256 (Spring 1969).
5. Copies of this report may be obtained from AEC's Division of Isotopes Development, and it was published in *Isotopes and Radiation Technology*, 6(2): 164-174 (Winter 1968–1969).
6. U. S. Department of Commerce, Guide to Services, Suppliers, and Research on Food Irradiation, available from U. S. Department of Commerce, Sales and Distribution Branch, Washington, D. C., 20230 ($0.50).

Radioisotopes: Production and Development of Large-Scale Uses. Part II: Applications

Editor's Note: This is the second part of USAEC Report WASH-1095, which is being reproduced with minor editorial changes, since most of it is appropriate to the scope of *Isotopes and Radiation Technology*. Part I was published in *Isotopes and Radiation Technology*, 6(2): 131-144 (Winter 1968–1969).

Space Power Systems

Background

Applications. Isotopic heat sources are used to supply thermal energy to space electric-power systems. Four generators (SNAP-3, SNAP-9A)[1] have already been operated in Department of Defense (DOD) navigation satellites, and units now under development were scheduled to be delivered in FY 1968 for use on the Nimbus-B satellite (SNAP-19)[2] and the Apollo Lunar Surface Experiments Package (ALSEP, SNAP-27)[3] to be left on the moon by Apollo astronauts who land there. Another generator (SNAP-29)[4] is being developed under AEC sponsorship to meet several possible DOD and NASA requirements for systems of 3- to 5-month lifetimes. Important characteristics of these generators are summarized in Table 1, and these projects plus the technology investigations being conducted in support of these system-development programs are described in more detail in the following sections.

Current Status and Performance Requirements. *Lifetimes of Interest.* For long-life space missions (greater than a few months), the radioisotope–thermoelectric generator (RTG),[5] fueled with ^{238}Pu, is the current state-of-the-art isotopic power system. Polonium-210 fuel is also under development for mission life approximating the half-life of ^{210}Po (138 days). Plutonium-238 and ^{210}Po are alpha emitters that require little or no shielding in unmanned missions and are relatively simple to handle on the ground. Nonnuclear competitors of these RTG systems are solar cells for

Table 1 Radioisotope–Thermoelectric Generators

	SNAP-3	SNAP-9A	SNAP-11	SNAP-17	SNAP-19	SNAP-27	SNAP-29
Applications: Environment	Earth orbit	Earth orbit	Lunar surface	Earth orbit	Earth orbit	Lunar surface	Earth orbit
Reference space mission	Navigation satellite	Navigation satellite	90-day surveyor	Small military communications satellite	Nimbus-"B"	ALSEP	Various
Power level, watts(e)	2.7	25	21–25	25	25	50	500
Specific power, watts/lb	0.59	0.93	0.83	1.0	1.0	1.5	1.0
Fuel*	Plutonium metal	Plutonium metal	^{242}Cm	^{90}Sr	Plutonium oxide	Plutonium oxide	GdPo
Conversion material	PbTe	PbTe	PbTe	PbTe and SiGe	PbTe	PbTe	PbTe
Safety criterions†	Burnup	Burnup	Intact	Burnup	Intact	Intact	Intact
Flight readiness	1961	1963	Ground demonstration 1966	Not being developed	1967	1968	Early 1970's

*Useful lifetimes for the ^{238}Pu systems are from 1 to 6 years; for the ^{242}Cm and ^{210}Po systems, about 3 to 5 months.
†Design criterions for atmospheric reentry after orbit decay or launch failure.

long missions; and solar cells, batteries, and fuel cells for shorter missions. A nuclear competitor, the reactor power system, will be competitive for long lifetimes, at power levels above a few kilowatts.

For short-lifetime missions, primary batteries or fuel cells have been used and will continue to be advantageous. However, the launch weights of batteries and fuel cells go up directly with integrated energy output. The fuel-consumption weight of nuclear sources is negligible and of solar systems is zero. Figure 1 illustrates this effect of lifetime on the weight of power sources. It is seen that batteries and fuel cells are quite heavy as primary power sources for long-life systems. On the other hand, nuclear and solar systems are uninteresting for very short lifetimes but are the main competitors for lifetimes longer than a few weeks. (The reactor system improvement in the 1970's should come from a combination of reduced unit weights with higher power and such technology improvements as higher efficiency.)

Selection Criterions. The most important criterions for comparing alternative space power concepts are weight, cost and availability, exposed area, reliability, and applicability to special employment situations. Efficiency of isotopic systems is important mainly because of its effect on other criterions, especially cost and fuel availability. These factors are discussed in the following paragraphs, especially from the point of view of their effect on development objectives for isotope power concepts.

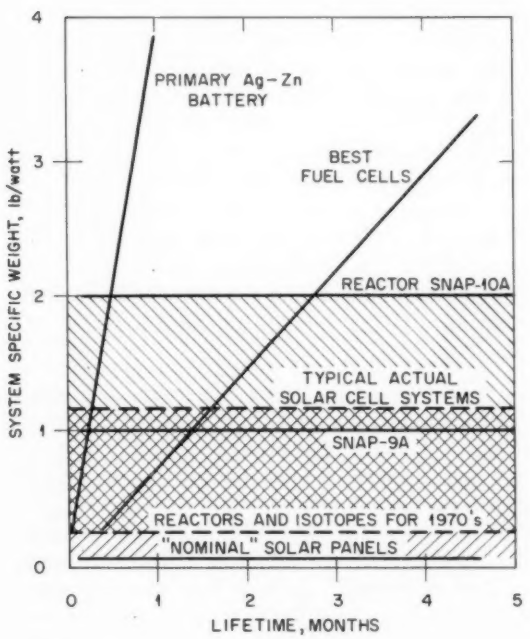

Fig. 1 Specific weight of power system as a function of lifetime, showing overlap of typical nuclear and solar systems of 1970's.

Weight. Typical weights of current and projected radioisotope and solar cell systems are shown in Table 2. At the subkilowatt power level required today, solar cell systems usually are lighter than isotope systems in cases where the solar-cell-system weight approaches the "nominal" panel weight, i.e., at a distance from the sun of 1 arbitrary unit (the distance of earth from the sun) and with the solar cells in full time, full sunlight; on the other hand, isotopes may be lighter where circumstances require use of unoriented systems (i.e., sufficient area of solar cells to intercept adequate sunlight regardless of the orientation of the spacecraft), or where the system must operate in the shade or far from the sun. Since the amount of incident solar energy varies inversely with the square of distance from the sun, the output of a given solar array will be, at the orbit of Mars, for example, roughly half what it is near Earth. As regards system cost, Table 2 indicates that isotope systems are more expensive than solar cell systems except where conditions are unfavorable for solar cells or if a cheaper fuel such as ^{90}Sr can be used instead of the currently proven ^{238}Pu. It is also seen that expected technology advancements, such as development of thermionics and the Brayton cycle, will tend to make isotope systems relatively more attractive.

Reliability. As regards reliability, there appear to be no inherent characteristics of solar cells or isotopic systems that give either one a clear advantage. Both isotope and solar cell systems have certain features that can potentially cause trouble, but these and the design adjustments to avoid trouble are well understood. In applications such as those in earth orbit where storage of electricity in batteries is required for periods when the satellite is hidden from the sun, the lifetime of a solar system is currently limited by the lifetime of the batteries, which is currently less than 2 years. This limitation does not exist with isotope systems.

Safety. A single safety criterion is that no undue hazard to people or property be caused by any foreseeable results of the launch. More specific design criterions are evolving.[6] In many isotope space systems designs, one of the most difficult problems is safe

Table 2 Specific Weight, Cost, and Efficiency of Isotope and Solar Cell Systems

	Approximate year available	Approximate specific weight, lb/watt(e)	Approximate system cost, $\$10^3$/watt(e)	Approximate overall system efficiency, %
Current RTG (SNAP-9A, -19, -27 with ^{238}Pu; no shielding required)	Today	0.7–1.0	13*	5
SNAP-29 with ^{210}Po	Early 1970's	1.0	1	5
Radioisotope thermionic concept (unshielded ^{244}Cm)	Mid-1970's	0.30	4	15
Radioisotope–Brayton (manned, shielded ^{238}Pu)	Early 1970's	0.5–1.0	3*	20–25
RTG's using ^{90}Sr fuel unshielded	Uncertain	0.7–1.0	0.5	5
Current solar cells (oriented)	Today	0.1–1.0	0.5–1.0	7–10
Solar cells in 1970's (oriented)	1970's	0.025–1.0	0.5	10
Solar cells (unoriented or with batteries for shade-time operation)	Today	0.4–1.5	1–4	2–3
Solar cells, full sunlight at greater distances (d) from sun than orbit of earth. (At earth, d = 1 arbitrary unit.)	Today or future	Varies as d^2	Varies as d^2	7–10

*Based on average cost for fuel of $600 per thermal watt, without fuel recovery after use.

return and ultimate disposal or recovery of the fuel. The fuel must be safely contained or disposed of in the event of a launch-pad fire, a return to earth on launch abort, or a short-lived orbit; finally, in successful missions, the fuel capsule must be predictably safe after months or years in high-temperature operation. Reentry heating, possible partial or complete burial after impact, and the impact itself are difficult to analyze and design for. Because of the long half-life of the most desirable fuels, it is unlikely that performance data on materials or working assemblies will be obtained, prior to operation, for the full performance period required. Consequently, a significant fraction of all development funding will continue to go into safety testing and analyses for all new systems developed.

Size. The size of solar systems is determined by the area required to intercept solar energy, whereas the size of isotope systems depends on the size of the radiator which disposes of excess cycle heat. Isotope systems at least as small as solar cell systems are available today and can be modified to obtain further size reductions by increasing radiator temperature, with small efficiency reductions.

Cost and Availability. The cost and availability of preferred isotopes are of serious concern to planners. This concern stems from the high cost of producing and processing the isotopes, the long lead times required for production, and the lack of exact information on probable mission specifications and schedules. The current cost of fabricating an isotope power system, including all parts and material except the fuel, is $500 to $2000 per electrical watt; for a 5% efficient ^{238}Pu or ^{244}Cm RTG, the fuel cost is about $12,000 per electrical watt. Thus the RTG costs are mostly costs of long-life alpha fuels. These fuel costs are expected to be significantly reduced by increased efficiency and improved processing techniques and by developing a cheaper fuel such as ^{90}Sr. Cost and availability of fuels are discussed in more detail under Production, in Part I, which appeared in the previous issue.[7]

Special Cases. As noted, the solar cell–battery combination is the best power system for many long-life missions. However, the wide variety of potential missions in the national space program include special conditions which particularly favor isotopic, solar, or reactor systems. The following is a brief discussion of some of the more important cases:

Lack of sunlight.—Solar systems must be in direct view of the sun, or batteries must be provided with additional solar cells to charge them during sunlight hours. Isotope systems are not restricted by lack of sunlight. This limitation occurs in three categories of missions: In most earth orbits, the satellite is hidden by

the earth for some fraction of each orbit. Batteries for low-altitude applications can account for more than 50% of the total system weight. In interplanetary and out-of-ecliptic probes, solar cells will be reduced in effectiveness with the square of the distance from the sun. For example, the area of solar panels for a given power level at the orbit of Jupiter will be 27 times as large as on Earth. Other applications, such as on the surface of the moon, favor nuclear systems for missions requiring operation during periods of darkness (e.g., the 350-hr lunar night).

Low area requirements.—Nuclear systems can be designed to present a lower frontal area than solar systems. This could be an important advantage in certain classes of military surveillance systems where desirable low altitudes lead to high atmospheric drag penalties, and in missions in which large solar cell areas interfere with antennas and other equipment, or make packaging within a launch-vehicle envelope difficult. (Propellant required to overcome drag, or reduced lifetime without drag compensation, is a function of frontal area.)

Insensitivity to radiation.—Nuclear systems are inherently less vulnerable to the belts of trapped electrons that surround the earth. These belts could be intensified by future high-altitude nuclear detonations.

High-temperature environment.—Isotopic systems are relatively insensitive to environmental temperatures. For example, close to the sun or in the noonday heat on the lunar surface, solar cells would operate at reduced efficiency as their temperature increased; but isotope systems would suffer much less loss of efficiency.

High-radiation background.—Unless shielding is provided, radiation from the nuclear source can interfere with some types of radiation-sensitive experimental equipment.

High power.—Because of the high cost of long-lived alpha emitters and the favorable weight of reactors at high power levels, it appears that reactors will be preferred over both isotopes and solar cells for many of the long-life, tens-of-kilowatts space power requirements of the future. For the shorter missions (about 3 months), ^{210}Po (Ref.8), and possibly ^{170}Tm (Refs. 9 and 10), which offer advantages of low radiation shielding (compared to reactors) plus low cost, may be competitive into the kilowatt range. Improved solar cells may also still be attractive for missions at a few tens of kilowatts.

Importance of Temperature and Efficiency. Isotope systems could be materially improved with higher conversion efficiency. The fuel inventory, which to a first approximation represents the cost of the system, is reduced directly in proportion to an increase in system efficiency. Weight and radiator area vary approximately inversely with system efficiency. Other important characteristics are similarly benefited by higher efficiency.

Higher efficiency can be obtained by increasing the heat-source temperature and developing a more efficient power conversion technology. Since all isotopic power systems produce power by the flow of heat, overall efficiency is proportional to their Carnot efficiency (E):

$$E = \frac{T_h - T_c}{T_h}$$

where T_h = mean power conversion inlet absolute temperature, and T_c = mean power conversion outlet absolute temperature.

Since T_c cannot be reduced indefinitely without causing unacceptable increases in radiator area, the only way to improve Carnot efficiency is to increase T_h, or in terms of technology, to increase fuel surface temperature and power-conversion-system temperature capability.

Figure 2 illustrates the dependence of ideal thermoelectric-system fuel inventory on mean hot junction temperature. With two-stage (SiGe and PbTe) thermoelectrics, increases from the 1000°F hot junction temperature of SNAP-19 to about 1600°F could roughly halve the fuel-inventory requirement, which would almost halve system cost.

The second approach to greater efficiency and reduced weight and area is to develop more-efficient concepts for converting thermal energy to electricity. Some of these advanced power conversion concepts (e.g., thermionics) require high temperature in order to be attractive at all.

Objectives

The objectives of the space isotopic power development program may be stated as follows:

1. To increase fuel-capsule operating-temperature capability and thus achieve increases in system efficiency and reductions in weight.
2. To develop reliable, more-efficient power conversion concepts.
3. To investigate and develop methods of safe employment and ultimate disposal of space isotope systems.
4. To reduce isotope-system costs.

5. To develop the power systems or subsystems required by user agencies for specified space missions or classes of missions. Wherever possible these requirements will be fulfilled with combinations of standard modular systems and components to be developed.

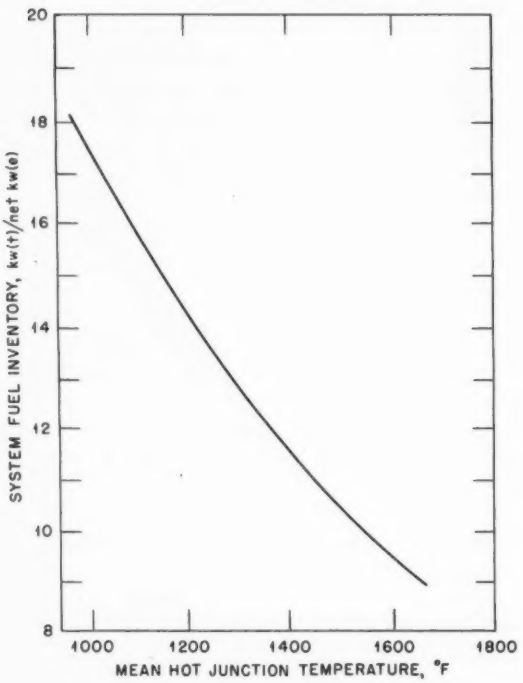

Fig. 2 Effect of hot junction temperature on fuel inventory of thermoelectric systems (optimized for minimum weight).

Program Plan

The program includes projects for the development of several categories of space power systems and technology projects in support of one or more of these categories.

Based on analysis of the above factors and what is known about likely missions, three categories of isotope power systems, characterized by power level and specific development problems, may be identified:

1. RTG's that employ integrally contained heat sources, radiatively or conductively coupled to thermoelectric converters, in turn cooled by heat conduction to radiative heat disposal surfaces. This category includes all the generators launched or scheduled to be launched during the 1960's. Power levels of these current systems are under 80 watts, but the concept seems to be practical up to about 100 watts. Following the SNAP-19 modular approach, new developmental concepts, including the NAVSAT unit, will emphasize modular designs to meet the widest possible range of potential requirements.

2. Modular RTG's for approximately the 100- to 1000-watt power range. This power range is transitional between the small, low-efficiency, self-contained, cylindrical, finned, static (no moving parts) systems of category 1 and the more complex, high-efficiency, dynamic systems being developed for high-power applications of category 3. The category 2 power system being developed today is SNAP-29, which has a convective heat-transfer system that cools the thermoelectric cold junction and disposes of the heat in a separate radiator located in some convenient location on the skin of the spacecraft.

3. Systems with separately packaged heat sources, power conversion machinery, and heat disposal subsystems, applicable to power levels above about 1000 watts(e). The system currently under development in this category is the isotope–Brayton 5.5-kw unit. At the high power levels of category 3, high-efficiency power conversion machinery is necessary in order to reduce the total quantities of long-lived fuels required.

Other categories or subcategories will be included as program requirements dictate. Power systems and technology projects currently being funded include the following:

Category 1 Systems. SNAP-19 generators are designed to supply a minimum of 50 net watts(e) to the Nimbus-B satellite for at least 1 year in orbit. The design calls for two 25-watt cylindrical modules, mounted in tandem on the Nimbus spacecraft.

SNAP-27 is a one-module cylindrical RTG to supply a minimum of 56 watts for 1 year to the ALSEP. Deliveries of two fueled systems, two backup units, and an extra test unit were planned during 1968. Three additional flight units will be delivered during FY 1969 for follow-on Apollo program missions.

The NAVSAT generator is an RTG being developed to meet the needs of an advanced DOD navigation satellite, using ^{238}Pu fuel.

Category 2 System. SNAP-29 is being developed for a class of potential national defense missions. It will be fueled with ^{210}Po, as GdPo, and is designed as modular units that may be combined to produce power in multiples of 100 watts(e).

The SNAP-29 project is in the stage of system technology development. Satisfactory test results could lead to full-scale ground-test-system development and a possible flight-system program.

Category 3 System. The AEC and NASA are cooperating in a joint program to develop and test a 5.5-kw(e) isotope–Brayton cycle power system[11] for space power applications of the late 1970's. The power conversion system will be of the closed-cycle Brayton

concept which has been under development at NASA Lewis Research Center for several years; the heat-source development is primarily a responsibility of the AEC and is a part of a continuing high-temperature isotopic heat-source program.

The AEC plans to deliver, for 1971 ground test at the NASA Plumbrook facility, a 25-kw(t) ^{238}Pu heat-source and test package. NASA will integrate this heat-source package with its power conversion system, and operational tests will be conducted under simulated space conditions.

One preliminary design concept being considered results from a study Oak Ridge National Laboratory performed for NASA. An AEC contractor has been selected for a capsule fabrication development program, the first step in the heat-source development. Additional technology development activities will be initiated, and a heat-source contractor will be selected in the near future to perform an overall heat-source design and conduct the integrated heat-source development program.

Space Power Systems Technology Projects. *Multihundred-Watt-Generator Studies.* The recently completed multihundred-watt-generator engineering study considered the feasibility of constructing an efficient RTG with the capability of reentering the earth's atmosphere, impacting the earth within a previously designated safe disposal area, and remaining intact after impact. The generator system was sized to use either ^{90}Sr or ^{238}Pu. The generator itself has a power-to-weight ratio greater than 1 watt/lb, but the controlled intact reentry requirement adds additional weight due to heat shields and the reentry control mechanism. Further design and development work is now under consideration.

Strontium-90 is attractive chiefly because of its low cost and ready availability. Radiation from the ^{90}Sr requires heavy shields for use in space, or results in a certain amount of inconvenience in remote-handling equipment and procedures at the launch pad. Development of a launch-pad handling concept which is compatible with launch operations, combined with a highly reliable capability for intact reentry, appears to be required if ^{90}Sr is to be used in space systems.

Space Heat-Source Development. In the development of advanced fuel-form technology, for all categories of advanced power conversion systems and for propulsion thrusters, the fuel surface temperature goals are as follows:

Thermoelectric (PbTe radiatively coupled), 1800°F
Advanced Rankine, Brayton, and auxiliary propulsion thrusters, 2000°F
Thermoelectric (SiGe and cascaded), 2200°F
Thermionic, 3250°F
Primary propulsion thruster, 3650°F

Qualification of a fuel form for use at a particular temperature involves characterization of the fuel form and determination of its compatibility with its container in the operating environment.

The chemical, nuclear, and physical characteristics of ^{238}Pu fuel forms are fairly well known. Compatibility testing to determine reaction rates between the fuel form and the primary materials of containment has been underway at 1800°F for some time and is nearly completed. Testing at 2750°F began in mid-1967. Long-term compatibility testing is essential to assure fuel containment during and after the mission.

Fuel forms of ^{210}Po are compatible with selected containment materials for at least 200 days at 1800°F. This demonstrates the operability of ^{210}Po for space missions of limited duration (100 to 150 days) operating at temperatures less than 1800°F. However, investigations of the ^{210}Po fuel form are not yet complete. Gadolinium polonide and the coated particles are still under consideration.

Space Power Conversion Technology. Space electric-power conversion technology is being developed by the AEC in close coordination with several other agencies. Included are improved thermoelectric generators that have the advantage of requiring few or no moving parts; dynamic turbomachinery, which uses moving parts to obtain increased efficiency; and thermionics, which will require high heat-source temperatures but should attain moderately high conversion efficiencies without the disadvantage of rotating machinery.

Thermoelectrics. All nuclear space power systems launched to date or scheduled for launch employ thermoelectric couples operating at hot junction temperatures below 1100°F. The projects for improving this technology involve optimizing to provide greater compactness and metallurgical stability, and extending operating temperatures from the present 1100°F into the 1100 to 1800°F range. The main thermoelectric technology projects are as follows:

The "*Lightweight Generator*" project is developing a converter technology that should yield very-low-weight systems using PbTe couples. Heat is received by radiant transfer from the fuel capsule; it

flows through the thermoelectric semiconductor pellets, which are highly optimized in geometry to take best advantage of PbTe low-temperature performance characteristics. The heat-disposal surface is a thin-foil radiator bonded directly to the thermoelectric cold junction. This technology appears to be adaptable also to systems in the hundreds-of-watts range, using heat pipes for heat transfer. Two-couple submodules have been operated for more than 14,000 hr with low performance degradation during steady-state operation. A life-limiting degradation of hot junction bonds was recently discovered to occur at about 14,000 hr. Corrective measures have been taken and are being verified. Development of this technology is continuing, and investigations of methods of cascading with higher-temperature thermoelectrics are being initiated.

Current isotope–thermoelectric generators use radiative or conductive heat transfer from the fuel capsule to the thermoelectric hot junction. The cold junction is cooled by conductive heat transfer to fins that radiate the excess heat to space. As power levels increase, the design of compact generators will demand that the heat to and from the thermocouples be transferred by convection. In a so-called *compact thermoelectric* generator, the thermocouples are installed within the walls of a heat exchanger that transfers heat from the source coolant loop through the thermocouples to a heat-disposal loop. This arrangement consolidates the converter into a small heat-exchanger package rather than spreading it out around a heat source or in a radiator; hence the name "Compact Converter." Development and qualification testing of generator modules have been under way since 1965.

Advanced SiGe modules will be developed in a program of investigation of improved hot shoe materials, fabrication techniques, and optimization of materials and bonds. Operational limitations in air and vacuum will be determined in terms of time, temperature, and materials compatibilities.

Another thermoelectric concept, which has been successfully used at 1000°F in the SNAP-10A reactor power system, is the so-called *advanced direct-radiating converter.* In this approach, heat is transferred from the heat source by pumped liquid metal (NaK), which flows within tubes to which the thermocouples are bonded. The NaK heats the hot junction; radiator segments mounted at the opposite end of the SiGe thermoelectric pellets remove the excess heat and radiate it to space.

Several modules have been tested for more than 2 years at 1300 to 1400°F hot junction temperatures; long-term testing is planned to be continued through FY 1970.

In the *cascaded thermoelectric* concept, two stages of thermocouples would be placed between the heat source and the heat-disposal system. This would allow the use of SiGe thermocouples in their temperature region of best performance (1000 to 1900°F), and PbTe in its best region (450 to 1000°F). By such a combination, efficiency approaching 10% may be achievable once the necessary high-temperature heat source and SiGe technology is available.

Thermionics. Thermionics promises efficiency of 10 to 20%, without the need for dynamic machinery, assuming that the required high operating temperatures can be achieved. The preliminary design of a ^{244}Cm-fueled thermionic module was completed in FY 1967. Development work has been deferred because of budget priorities. The plan was to proceed with the development contract in mid-CY 1968, leading toward a fueled ground test demonstration in the early 1970's.

Dynamic Machinery. AEC has done development work on two fairly low-temperature dynamic conversion devices that can yield improvements in efficiency and specific weight: the mercury vapor combined rotating unit (CRU) of the SNAP-2 (Ref.12) concept; and the organic Rankine cycle.[13]

A 3.5-kw(e) combined rotating unit (CRU), with the turbine, alternator, and mercury pump all on one shaft, has been developed for possible use with large isotope heat sources. This *mercury Rankine cycle* power conversion system would have an efficiency of 6 to 10%. It operates on 1200°F superheated mercury vapor. Emphasis was placed on development of the CRU, since other components such as boilers and radiators are less complex.

Approximately 2 years of CRU test time was accumulated in working out bearing and rotor dynamic problems. A reference-design CRU operated for 5000 hr, an adequate lifetime for potential space missions of the early post-Apollo era. The testing was to be completed during 1968.

A potentially attractive space dynamic system, which would not require the high temperatures usually associated with space operation, is the *organic Rankine cycle.* It derives its name from the use of an organic working fluid instead of liquid metal. Chemical instabilities of the organic fluid appear to limit its peak temperature to the range of 600 to 700°F, but favorable vapor pressure and polytropic expansion characteristics should result in attractively high power-conversion-cycle efficiency.

The present program will evaluate the practicability of the organic cycle. Various alternative organic working fluids are being evaluated. Data on allowable working temperatures and preferred bearing and pump configurations should allow preparation of a reference design in the late 1960's and initiation of a component development program if the concept still looks attractive.

The *Brayton cycle* uses gaseous working fluids. It is capable of achieving high thermal efficiency, and the use of a single-phase working fluid avoids some of the problems inherent in the two-phase Rankine cycle. Use of inert gases (or a mixture thereof) avoids almost all corrosion.

The reliability of long-term operation of rotating machinery with gas-lubricated bearings is still not established, but the cycle promises efficiencies in excess of 20%. However, low radiator temperatures are required if maximum efficiency is to be attained, which means high radiator areas. Turbine inlet temperatures of at least 1600°F are desirable, considerably in excess of that achievable with current heat-source technology. A 5.5-kw(e) modular gas bearing loop is being developed for electrically heated tests in 1968–1969. These components will be incorporated into the NASA–AEC joint-system program discussed earlier.

Space Nuclear Safety. The power-system projects are supported by a thorough nuclear safety program. Table 3 describes the status of approvals of isotopic systems for use in space. The parametric conditions already approved and the progression toward more advanced systems are evident in this table. To provide this safety support, a nuclear safety program consisting of two types of activities is being carried out: (1) System-Oriented Work—activities conducted by the AEC safety organization and its prime contractor, Sandia Corporation, in support of specific systems, and (2) Supporting Safety Research and Technology—activities applicable to several systems and contributing to a basic technology that will be useful in future space power system developments.

System-Oriented Space Nuclear Safety. These projects include both space power systems and other types of space isotope applications, such as safety analysis of isotope sources used in propellant tank gages and tracers for space experiments. In some cases, safety investigations pace the evolution of overall system design concepts.

Supporting Safety Research and Technology. Safety criterions for specific radioisotopes or for classes of space applications are being formulated. Advanced safety-technology areas include standardization of methods of safety analysis; improvement of postmission disposal methods; assessment of the capability to track nuclear-powered spacecraft in the event of an abort and to locate and to recover sources in the event of an accident; study of methods of eliminating or reducing launch safety uncertainty and methods of designing systems which are passively safe under all adverse conditions.

Terrestrial Power Systems

Background

Applications. Isotopic power systems (SNAP-7A–E)[14] using ^{90}Sr heat sources and lead telluride (PbTe) thermoelectric power conversion are in use in several marine and remote terrestrial sites such as navigation beacons, weather buoys, polar-region unattended weather stations, and underseas oceanographic installations. These first-generation units have demonstrated the feasibility of long-term, unattended operation, and they point the way toward development of truly competitive devices.

As a prerequisite to the initiation of advanced development programs, considerable effort is devoted to the evaluation of potential applications, keeping in mind alternative energy sources, environmental factors, operating lifetimes, and economics. From such continuing evaluations, performance specifications are established which, if attained, could result in the extensive use of isotopic power sources. The systems being developed have a tremendous potential for application. For example, a worldwide weather-buoy system such as that being considered by the World Meteorological Organization, the Panel on Ocean Engineering of the President's National Council on Marine Resources Engineering Development, and the Weather Bureau, could involve the deployment of many hundreds of unattended buoys throughout the world. Isotopic power systems have been identified as primary candidates for these applications as well as for many hundreds of radio and TV microwave repeater stations. Also, hundreds of offshore oil and gas platforms over the world could utilize isotope systems for navigational aids. Even if only a small fraction of this potential is realized, its needs could exceed the currently forecasted ^{90}Sr availability. Similar situations exist in the area of underseas and other

Table 3 Status of Flight Approvals of Isotopic Sources

	Isotope	Approximate activity level, curies	Capsule operating surface temp., °F	Fuel form	Thermal power, kw(t)	Comments
1. SNAP-3A	^{238}Pu	1,800	950	Metal	0.060	Two units launched 1961, long-lived* orbits. Designed for complete burnup on reentry if short orbit occurred. ISR† approved.
2. SNAP-9A	^{238}Pu	15,000	950	Metal	0.5	Three units launched 1963–1964. Two achieved long-lived orbits, one reentered atmosphere on launch trajectory due to guidance failure, burned up as designed, on reentry. ISR approved.
3. SNAP-19 (25-watt module)	^{238}Pu	18,000	1400	PuO_2 (microspheres)	0.6	Scheduled for launch on Nimbus-B satellite early 1968. Designed for intact reentry in event of abortive launch or short orbit. ISR approved.
4. SNAP-27	^{238}Pu	45,000	1400	PuO_2 (microspheres)	1.5	Scheduled for launch on first Apollo lunar landing. Protected to ensure capsule remains intact in event of abort reentry. Interim ISR by 9/1/68.
5. SNAP-29	^{210}Po	800,000	1800	GdPo	25	Scheduled for ground test in 1970 with intent to be used in short orbits in space in early 1970's. Preliminary ISR by 7/1/68. Designed for intact reentry.
6. Isotope–Brayton system	^{238}Pu	750,000	2200	PuO_2 (microspheres)	25	Scheduled for ground test in 1971 with intent to be used in space in mid 1970's. Intact reentry.
7. Water recovery	^{238}Pu	8,400	150 and 1200	PuO_2	0.28	Makeshift encapsulation, safe only for ground test.
8. AMSA unit	^{147}Pm	200,000	600	Pm_2O_3	0.060	USAF has applied for licensing under routine isotope licensing procedures for atmosphere operation. USAF will perform its own safety analysis for the intended mission.
9. Radiation sources of Apollo‡ Surveyor, OSO, biosatellite	Various	Insignificant	Approximate ambient	Various	Insignificant	Insignificant safety hazard involved due primarily to the small amount of isotopic fuel in these units.

*A long-lived orbit is one that will last several times the half-life of the isotope.
†Interagency Safety Review.
‡See above for SNAP-27 thermal source, also launched with Apollo mission.

unattended power applications, wherein hundreds of units could be required annually for acoustic and sonar beacons, deep-sea transponders, seismic stations, tsunami (seismic) gages, oceanographic instrument packages, cable boosters, and passive sonar listening sites.

Competitive Factors. The use of isotope power systems is dependent on their economic competitiveness with conventional power sources. The relatively high procurement cost of isotopic systems must be balanced against their low operation and maintenance costs over a long lifetime.

Competitive factors are somewhat different in the use of isotopic systems in ocean-bottom and deep-sea applications. In these instances, isotopic power may be the only practical means of providing reliable power,

particularly where long life is required (about 12 months or greater).

The results of some of these analyses are summarized in the following paragraphs:

Remote Surface Applications (SNAP-23). The following are representative of remote surface applications that have been analyzed from an economic viewpoint:

Offshore Oil. Power is sold to operators of offshore oil and gas platforms in the Gulf of Mexico at an average cost of $10 to $12 per kilowatt-hour. The cost is significantly higher in other areas of the world. The 60-watt SNAP-23 generator has as its objective an operating cost of less than $10 per kilowatt-hour exclusive of any fuel buyback consideration. As oil operations extend farther offshore, the average cost of nonnuclear power will increase sharply due to logistics, whereas the cost of isotopic power should be nearly independent of this factor.

Coast Guard Buoys and Lighthouses. The Coast Guard has extensively evaluated the use of isotopic power and has concluded that, if the SNAP-23 specifications are met, the higher-power applications (50 to 100 watts) associated with lighthouses are prime candidates for advanced isotope power systems. Isotopic power should be especially attractive economically for lighthouses located along the Alaskan coastline, where servicing is expensive and hazardous.

Weather Buoys. The U. S. Navy NOMAD weather boat is the forerunner of an unattended network of data-gathering weather stations to be moored on the oceans of the world. Buoys using commercially available diesel generators and batteries must now be serviced at least every 12 months. Dispatching a Navy vessel to recover and service a mid-ocean buoy has been estimated to cost on the order of $50,000. The capital-cost objectives for a 60-watt SNAP-23 ^{90}Sr power system (10-year lifetime) is on the order of $50,000 to $60,000 exclusive of fuel buyback considerations. The SNAP-23 performance and cost objectives are based on what the Navy and other potential users have indicated to be attractive for operational use.

Aircraft Marker Beacons. The Federal Aviation Agency (FAA), in its development of small-airport instrument landing systems (ILS), has difficulties in providing reliable power for aircraft beacons, some of which are located up to 10 miles from aircraft touchdown. Batteries, diesels, and other portable power systems are prohibitively expensive to use owing to servicing requirements. The currently acceptable solution to the problem is to construct an electrical substation at a cost (including roads) of about $5000 for each mile from the primary power line. Based on projected power-supply procurement costs, a 5- to 10-watt isotopic power system would be competitive in those instances where the substation is more than 2 miles from the primary line. The FAA estimates on an economic basis that 25 to 50% of the small airports could effectively utilize isotopic power sources. Airports located outside the United States offer even greater promise of use.

Studies of these four potential applications and others, such as oceanographic buoys, microwave repeater stations, unattended seismological stations, and military communications systems, have led to the following criterions:

Unattended operating lifetime: high probability of 10 years
Electric power: 25 to 100 watts
Dose rate, max. (1 m from surface): 10 mrems/hr
Operating environment: free circulating air, 75°F, 1 atm, 50 to 100% relative humidity
Fuel: ^{90}Sr
Maintenance: field maintenance required
Power cost (excluding transportation, installation, and fuel buyback): $10/kw-hr
Weight (60-watt unit): less than 1000 lb

Although these characteristics appear to be attainable, they are significantly beyond current technology and will require an extensive research and development (R&D) effort.

Underseas Applications (SNAP-21). In an unattended underseas application, isotope power offers a unique advantage: competitor power concepts will do the job for only up to a few months and then only at great expense. Analyses of these applications led to the following development criterions:

Electric power: 10 to 20 watts
Weight (10-watt unit): 600 lb
Seawater pressure: 0 to 10,000 psi
Water temperature: 28 to 41°F
Moisture: 100% relative humidity in seawater
Life (minimum): high probability of 5 years
Fuel: ^{90}Sr

A premium is being placed in this program on the use of rigid quality assurance and reliability techniques coupled with rigorous and long-term testing of all materials and components under laboratory and simulated environmental conditions. Upon completion of the development activities, cooperative testing programs will be arranged with interested user

organizations to provide long-term test data in various environments.

Milliwatt-Generator Applications (SNAP-15). **Unattended Instrument Power.** For underseas electronic devices such as cable boosters, sonic pingers, and other underseas instruments, it appears that an isotopic power system capable of a 5-year life at $2000 per 0.5- to 1.0-watt(e) unit would be competitive with currently available battery-powered units. Battery life is now less than 1 year.

Cardiac Pacemaker.[15,16] The pacer is a device which provides small repetitive electric pulses to stimulate the heart and cause it to beat at a constant rate. It is implanted within the patient's body—usually in the abdomen or under the pectoral muscle, although other implantation sites are sometimes chosen. Presently available units are replaced surgically every 18 to 24 months because of the limited lifetime of the mercury-cell battery power supply.

A long-lived ^{238}Pu system would eliminate this life-limiting factor, and repetitive surgery with its associated high cost and physical strain would be significantly reduced. The objectives for the isotope-fueled pacer are high reliability for at least a 10-year lifetime, total weight less than 100 g, and an average power of 162 μw(e). The reduction of costly surgery and hospitalization and the remaining value of the unit at death would lead to substantial cost savings to the patient to compensate for the high cost of the improved unit. The basic generator concept is expected to have additional important biomedical applications including muscle stimulation for paralyzed limbs.

Various Milliwatt Applications. No competitors to isotopic power exist for a group of military and paramilitary applications. These applications will require typically 1 to 10 mw from a system having a total weight less than 1 lb. Reliability must be as high as 0.99 with 90% confidence, for 5-year life. Feasibility for these applications is being demonstrated in the SNAP-15A program. Due to handling requirements, ^{238}Pu fuel sources are required in these systems.

Kilowatt System (1 to 20 kw). A large number of potential requirements, particularly underseas programs and remote arctic activities, can use isotopic energy in the low kilowatt power range. Although detailed studies have yet to be completed, the possible alternative power sources for applications such as these appear quite limited. Competitors are diesel generators (which require considerable logistical support), short-lived battery systems, fuel cells, and possibly nuclear reactors. The first phase of a program, initiated in FY 1968, consists of extensive application engineering and parametric design studies. It will identify specific types of applications, alternative power sources, performance objectives and criterions, and economics, including requirements for electric and mechanical power and for heat. Fuels under consideration are ^{90}Sr, ^{60}Co, and ^{144}Ce. Dynamic as well as static power conversion systems will be considered.

Objectives

Isotopic Power Program objectives for terrestrial applications are as follows:

1. To develop, test, and demonstrate radioisotope power systems for general-purpose oceanographic and terrestrial applications, specialized military and commercial applications, and specialized medical applications.
2. To continue broadly based technology programs applicable to various power systems necessary to bring about improvements in cost effectiveness, power conversion efficiency, reliability, and lifetime.

Program Plan

Power-System Projects. *10 to 200-Watt Isotopic Power Systems.* For this power range the AEC program consists of two projects, SNAP-21 and SNAP-23. SNAP-21 is a two-phase program for the development of isotopic power systems (10 to 60 watts) for deep-sea and ocean-bottom application. The design and component development effort on the basic 10-watt system has been successfully completed. In the currently approved phase of development, a series of fueled prototype ^{90}Sr power systems will be fabricated, assembled, and extensively tested. If the concept proves to be satisfactory, the 10-watt design concept can be extended to higher-power versions. Arrangements are being made with the Navy for testing one or more prototype generators in both simulated and actual environments.

The SNAP-23 program is directed toward development of terrestrial (surface) systems. Work during 1967 included the development of highly efficient segmented thermoelectrics and readily fabricable, reproducible system components, and the standardization of major components adaptable to varying power levels from 25 to 100 watts. The program will encompass the application of proven technology and components to systems of both higher

and lower power and will include a fabrication and test effort. Test arrangements with users, similar to SNAP-21 arrangements, are planned. The reference design will provide a 60-watt power source for various terrestrial environments.

Milliwatt Isotopic Power Systems. An extensive applications engineering and parametric design study was completed in FY 1966. From the data obtained in this study, development programs are scheduled to be initiated in FY 1970. They will culminate in the fabrication, testing, and demonstration of proven prototype systems in areas where they are expected to find greatest use.

SNAP-15A is a small milliwatt device being developed for use in weapons. Approximately 3 g of ^{238}Pu is used to provide a 400°F hot junction temperature to 1300 metallic thermocouples. No shielding is required. The 5-year-life unit is designed to provide 1.55 mw(e) at a voltage of over 4.5 volts. To date, 21 fueled prototypes have been extensively tested to validate the extremely high reliability associated with the classified reference application. These systems are also attractive for communications and microelectronic control applications. Improved units are currently being fabricated for further testing.

Also in the milliwatt range, SNAP-15C was developed to provide power for use in a classified application.

Microwatt Isotopic Power Systems (Pacemaker). In FY 1966 the AEC initiated a program to develop a plutonium-fueled cardiac pacemaker.[16] The first phase of this two-phase program will concentrate on detailed engineering design and component development and will culminate in the assembly and short-term performance testing of experimental models. The objective of this phase is to develop working prototypes which conform to the performance and medical compatibility specifications and which can be adapted easily to the several electronic pacemaker designs that are now commercially available.

As presently conceived, the entire pacemaker system will weigh 97.5 g and be 6 by 4.87 by 2.8 cm in size. Approximately 0.30 g of ^{238}Pu metal will be used as fuel. The generator is to provide a 162-μw output over a 10-year lifetime. The second phase (to start in FY 1969, assuming a successful Phase I) will include extensive fabrication and test efforts (including animal in vivo tests) to demonstrate the reliability and lifetime requirements associated with a surgically implanted nuclear power cardiac pacemaker.

Technology Program. In addition to programs to develop systems technology, a supporting materials and component technology program is being conducted. This technology development program currently includes work on insulation, thermoelectric modules and materials, fuels development, and safety.

Vacuum and Fibrous Thermal Insulation. The vacuum insulation system consisting of thermal reflective foils interspaced with insulation materials has been developed commercially for cryogenic applications. It is being improved for use at high temperatures. A vacuum insulation system is being used in the SNAP-21 program, and the research effort is also applicable to that program.

Min-K fibrous insulation has been used for SNAP applications because of its relatively low thermal conductivity, good machinability, low cost, and structural strength. However, the material has degraded in air and has presented diffusion problems with surrounding materials. Technology work currently under way includes the analysis of numerous insulation materials and the development of production processes to provide an improved insulator. Min-K insulation may be used in powder form around the legs in the thermoelectric converter in both SNAP-21 and SNAP-23. Research and development in thermal insulation has direct application to these programs.

Pressure-bonded Segmented PbTe–BiTe Thermoelectric Modules. Segmented PbTe–BiTe thermoelectrics are capable of high efficiency and are being used in the SNAP-21 and SNAP-23 generator programs. A thermoelectric technology program is under way to produce high-performance segmented tellurides by hot isostatic pressing techniques. This effort is oriented toward reducing the high contact resistance that develops at the P-element hot junction causing power degradation with time. The program is also aimed to provide a means of bonding the segments to permit the fabrication of dense, uniform, thermoelectric materials.

Thermoelectric Materials. The thermoelectric materials development program includes studies of the high-temperature capabilities of thermoelectric materials; investigations of new concepts in couple and module design; performance and stability tests on thermoelectric couples being developed specifically for the terrestrial SNAP systems; evaluation of mechanisms associated with deterioration; and development of specifications, standards, and test criterions for couples and modules. The overall objectives of the program are

to improve generator efficiency, reduce weight and volume, and extend the temperature range.

Strontium-90 Safety. To provide full reliability and complete confidence in the deep-ocean application of SNAP devices, additional information is needed regarding the effects of the ocean environment on fuel and fuel capsules. Data to be obtained include rates and means of dispersement of fuel into the ocean should a fuel capsule be ruptured, and the effects of corrosion, erosion, currents, and depth on the capsule and surrounding components. Tests will be performed in the laboratory and in the ocean using hardware from the SNAP-21 deep-ocean thermoelectric generator.

Thermal Applications

Background

Applications. The thermal energy of radioisotope decay can be used for thermal conditioning, i.e., for maintaining and controlling temperature or for process heat, or can be converted to mechanical energy.

Applications of radioisotope heat to thermal conditioning, which have been or are being developed, include maintaining desired temperature levels in satellite and aircraft instrument systems, divers' wetsuits, and batteries. The use of radioisotope decay energy for process heat is currently being developed for such applications as distilling urine to recover potable water in manned spacecraft. Conversion of the heat released in radioisotope decay to thermodynamic energy is being investigated as a means of powering a totally implantable circulatory support system.

Current Status and Performance Requirements. Isotopic heat sources can offer a significant advantage over alternatives such as electric heaters since isotopic radioactive decay produces heat directly—no energy conversion with attendant loss of efficiency is involved. Isotope systems best serve applications in hostile or inaccessible environments, such as in space, in oceanographic systems, in isolated terrestrial uses, and for body implant where nonisotopic alternatives would impose reliability or logistic restraints.

Thermal Conditioning. Radioisotope heat sources for thermal conditioning should be inherently more reliable than electric resistive heaters, since electrical leads and connections, controls, and power conditioning equipment are not needed. Disadvantages of isotope units include the design inconvenience of being unable to turn off the heat when it is not needed. Electric battery power packs for diver-wetsuit-heater applications weigh 30 to 40 lb, have a discharge period of about 3 hr, and then require an 18-hr recharge. Isotopic thermal wetsuit conditioners weigh about 15 lb and require refueling only after about one half-life of the isotope selected. Thus, for periods longer than about 3 hr, isotopes offer unique advantages in this application.

Process Heat. Solar and isotope energy are efficient thermal-energy sources for spacecraft life-support systems on long-duration flights. Although solar energy is abundant and reliable, its use requires large areas for solar concentrators, close-tolerance solar attitude controls, and high-temperature energy storage systems for operation in the earth's shadow. Isotope systems appear to have the same advantages and disadvantages in these areas as in the category of thermal conditioning.

Mechanical Energy Systems. Several energy sources are under consideration to power an engine for circulatory support systems designed to replace or supplement damaged human hearts. Secondary batteries are well developed but require an external energy source for daily recharging. Biological fuel cells, although extremely attractive, have not been developed to practical usefulness. For these reasons, isotopes appear to be a promising energy-source candidate for this application.

Objectives

Program objectives are derived in most part from the role of the AEC in developing the peaceful uses of nuclear energy. The general program objective is to develop radioisotope heat sources and system modules in which the thermal energy is utilized directly or is converted into mechanical energy in a heat engine.

Program Plan

Circulatory Support System. An intensive study by the National Heart Institute recently concluded that an isotope-powered engine for circulatory support systems (i.e., a heart pump) is potentially capable of being totally implanted in the human body. Four conceptual design studies have been completed under contracts jointly funded by AEC and the National Heart Institute, on various radioisotope engines to supply mechanical power for fully implantable heart-assist devices, as well as possibly for total heart replacement.[17]

Animal implantation studies, using isotopic sources fabricated by the AEC, are also being conducted by the National Heart Institute. The results of these studies are vital to determining the radiation and thermal tolerances of the body, thereby defining the constraints that must be satisfied by the circulatory support system.

In addition, research and development work is being conducted on methods for obtaining ultrapure or "medical-grade" radioisotope fuels for such devices. Deleterious effects from the radiation and thermal outputs of the implanted radioactive source must be minimized. The radiation and thermal properties of various fuel forms of the candidate isotopes for this application, ^{238}Pu and ^{147}Pm, will be determined by parametric studies of the source radiation and thermal intensity as functions of quantity of pure isotope present, source geometry, source container materials, nonradioactive constituents, and radioactive impurities in the fuel form. The optimum combination of the least biologically objectionable fuel forms, source geometry, and containment materials will be identified. Methods for enhancing fuel purity to minimize extraneous radiations will be examined. For example, ^{238}Pu produced by present methods contains 1 to 2 ppm of ^{236}Pu. Special efforts will be initiated to study methods for reducing the content of ^{236}Pu, the precursor of ^{208}Tl, a hard-gamma emitter, and for reducing the content of low-atomic-weight nuclides that produce neutrons by (α,n) reactions. Emphasis in the ^{147}Pm development studies will be on investigating the feasibility of removing the hard-gamma emitter, ^{146}Pm, present in the fuel. By late FY 1969 it will be determined (1) if a fuel form of acceptable purity for this application can be produced and (2) if capability exists or can be developed to produce this fuel in quantity.

Integrated Life-Support Unit for Manned Spacecraft. A successful 30-day test was made of a radioisotope-powered [280 watts(t) ^{238}Pu] proof-of-principle unit for recovery of water from urine, washwater, and condensate.[18] The unit is capable of yielding about 2 gal of water per day, which is sufficient for two men. Early progress with this unit resulted in an investigation of the integration of the various life-support components, including carbon dioxide removal, temperature and humidity control, waste disposal, and respiratory support. Conceptual designs of integrated life-support units for manned spacecraft have been evaluated; and the detailed design, fabrication, and test of a prototype model are scheduled for completion by FY 1971. The applicability of the life-support system technology to manned underseas operations would also be investigated.

Heat-Source Development. Small thermal sources are under development for component heater applications. A 65-watt(t) ^{147}Pm heat source has been loaned to the Air Force to heat an aircraft instrument package.

A radioisotope-powered swimsuit heater for divers is being developed by the AEC for the Navy.[19] The best method of maintaining the body temperature of divers exposed to the cold of deep-ocean conditions seems to be by means of a circulating-water heater system. The diver would wear a suit embedded with veinlike tubes which would circulate warm water. The principle is the same as used in suits for astronauts and aviators. The heat to be supplied to the transfer fluid would come from a radioisotope backpack heater. The heater supplies approximately 400 watts(t), which is the amount needed to maintain body temperature at ambient temperatures of 45°F. The isotope-heated swimsuit is to be tested by the Navy in the Sealab III experiment.

Process Radiation

Background

Applications. Process radiation is the production or processing of chemicals and materials using ionizing radiation as a source of energy to produce chemical, physical, or biological change. Research in private industry has led to several commercial processes such as the production of ethyl bromide, cross-linked polyethylene film, polyethylene oxide of controlled molecular weight, and specialty graft copolymers in the fibers industry. The AEC program is directed toward broadening the base of technology associated with process radiation and identifying and demonstrating specific outgrowths of this base technology.

Competitive Factors. Some of the advantages of radiation as compared to alternative methods are (1) its ability to initiate a reaction at low temperature; (2) the fact that it is an external initiator which introduces no impurity into the system; (3) its ability to initiate reaction in the solid phase or a swollen solid phase; and (4) its ability to be used to treat a material in its final geometric form or in its final containers. However, desirable as some of these characteristics may be, successful applications of process radiation depend on

economic considerations; and this requires that any radiation process must be more efficient than alternative processes. Thus, in addition to demonstrating technical feasibility, it is often also necessary to demonstrate the economic potential of the radiation process. This involves development of efficient source design and engineering design specific for the radiation process. In summary, R&D work in this area must encompass research on (1) the basic chemical process, (2) source design, and (3) radiation engineering.

Objectives

The objective of the process radiation program is to advance technology that will assist the development of economically useful process radiation systems. A principal program function is to stimulate the commercialization of radiation processes.

Program Plan

In general, the process radiation program supports efforts to obtain basic technological information and radiation engineering data, and to show through selected demonstrations, if necessary, that the techniques work and are economically justifiable. The overall program consists of three parts: basic technology development, radiation engineering, and specific process applications, usually proceeding in that sequence.

Basic Technology Development. Effort in this category is directed toward the clarification of radiation phenomenons and reactions that are basic to the development of specific processes.

AEC is supporting research activities aimed at determining the basic mechanism of interactions of beta and gamma rays with specific chemicals. This effort is product-oriented in that potential chemical reactions are evaluated for efficiency of chemical conversion per unit amount of radiation energy and for purity of the final product. These determinations are fundamental to the evaluation of the potential usefulness of the reaction, since they are important economic factors.

Major areas of study are liquid-phase free-radical chain reactions with a major emphasis on polymerization and halogenations, reactions in the solid state or of liquid in solid substates, reactions at low temperature, and reactions at surfaces. Potential applications of radiation processing in this area include the impregnation of concrete with plastics to produce a concrete material that will be resistant to hot brine and to distilled water and serve as a potential construction material for water desalination processes and cross-country pipelines, and studies of olefin reactions with amines, alcohols, thiols, and silanes to yield new products.

Radiation Engineering. A substantial portion of the Process Radiation Development Program is devoted to the development of engineering data essential to the orderly adoption of radiation as an industrial process tool.

Source Development. At the present time, cobalt is the most important isotopic radiation source. Several cobalt radiation sources have been developed. Cesium-137 and ^{90}Sr are currently under active development as process radiation sources.

Engineering Process Data. Theoretical and experimental data are being obtained which characterize radiation fluxes for basic source configurations. This information is a prerequisite for facility and equipment design.

Specific Process Applications. Processes that emerge from the basic technology development effort showing definite promise and economic benefit are investigated further. In advancing specific process applications, AEC strongly encourages industrial technical and financial participation to keep research directed toward objectives that are of genuine commercial interest. Several specific process applications are currently under way.

Food Irradiation.[20] A primary goal of the AEC program is to develop to the point of commercialization the technology for the low-dose radiation process of preserving foods. Work is directed toward developing a limited number of products with good commercial potential through semicommercial-scale demonstration, and approval for consumption, by the Food and Drug Administration. A necessary part of the program is the development of prototype commercial food-irradiation facilities. Radiation facilities for food processing either in operation or under construction include four research irradiators, a grain products irradiator, an experimental on-ship irradiator, a mobile truck-mounted irradiator, a land-based fish-processing pilot plant, and two land-based fruit irradiators.

An international goal of the program is to participate with other nations in cooperative radiation pasteurization projects to combat worldwide shortages of food. Food irradiators have been or are to be

installed in Israel, Argentina, India, Pakistan, Iceland, and Chile.

Radiation-Processed Wood–Plastic Materials.[21] Radiation-processed wood–plastic materials have been under development by the AEC since 1961. These materials offer potential advantage over natural wood for some uses. The product is produced by impregnating wood with a liquid monomeric material (such as methyl methacrylate) and then irradiating it with gamma rays to convert the monomer to a hard plastic material. Conventional heat processing techniques are a competitive alternative, but it appears that the radiation technique offers a number of advantages.

Two private firms are now producing specialized radiation-processed wood–plastic materials in developmental commercial quantities, and a third has announced plans to do so.*

Radiation Synthesis of Polyethylene and Related Copolymers.[22] A process has been developed in which radiations can produce acceptable polyethylene under conditions that will reduce significantly the operating pressures currently used in the chemical peroxide-initiated high-pressure process and the quantity of highly specialized organic metallic salts used in the alternative commercial process. The radiation process offers sufficient promise from a cost and product-quality viewpoint to have attracted several industrial companies to undertake construction of pilot plants employing ^{60}Co.

Commission-supported work on polyethylene has been discontinued, and attention is currently focused on radiation synthesis of ethylene copolymers of potential interest and utility.

Radiation-Induced Emulsion Polymerization.[23] Studies in this area are primarily aimed at developing a process to produce latex materials used in water-base paint formulations. The radiation process can operate efficiently at low temperature (0°C), yielding a higher-molecular-weight product, which can impart greater wet-wear properties to the paint film. Residues of the catalyst or of excess monomer, which can be a problem with conventionally produced latex, are less of a problem with the radiation-induced polymerization reactions. The economic and practical feasibility of this process for industrial use is now under study.

*See also "Technical Progress in Wood–Polymer and Other Fiber–Polymer Combinations Around the World," p. 323, this issue.

Space Propulsion

Background

Applications. Radioisotope thrusters use the thermal energy produced by the decay of an encapsulated radioisotope to heat a propellant, which is exhausted through a rocket nozzle to produce thrust. These thrusters can provide relatively low thrust (10^{-6} to 10^{-1} lb) and high specific impulse (200 to 800 sec, depending on the propellant selected and the isotopic capsule temperature capabilities) in a simple, lightweight (10 to 100 lb) engine.

Currently, radioisotope thrusters are under investigation for primary propulsion and for spacecraft-attitude-control functions.

Competitive Factors. The weight of propellant which must be expended and the "inert" or "dead" weight of the system which must be carried along are the two key weight factors in the selection of space propulsion systems. A measure of the efficiency of propellant usage is the specific impulse (ISP), which is the thrust provided per unit of propellant flow. (Pounds of thrust divided by pounds per second of flow gives ISP units of seconds.) The specific impulse that can be delivered by a propellant is proportional to the square root of the ratio of its chamber temperature to its molecular weight.

Conventional chemical rockets achieve vacuum specific impluse around 350 sec with storable propellants and approach 450 sec for cryogenic propellants. Other propulsion concepts are the nuclear reactor (at high thrusts), the radioisotope-heated thruster, an electrical-resistance-heated jet, and an electric-arc jet. Figure 3 presents the theoretical specific impulse which could be delivered by such systems as a function of temperature for several propellants. More-advanced electrical propulsion systems can achieve higher specific impulses, ranging to 10,000 sec or more, but require large electric-power supplies to achieve useful thrust.

Other important comparison factors are equipment weight, reliability, safety, ease of development, and cost and availability.

Primary Propulsion Applications. Radioisotope-heated thrusters for primary propulsion must achieve a specific impulse on the order of 800 sec to compete favorably with high-energy chemical bipropellant competitors. This restricts propellant choice to hydrogen and requires thruster temperatures in excess of 4100°F. Typically, such thrusters would be built in

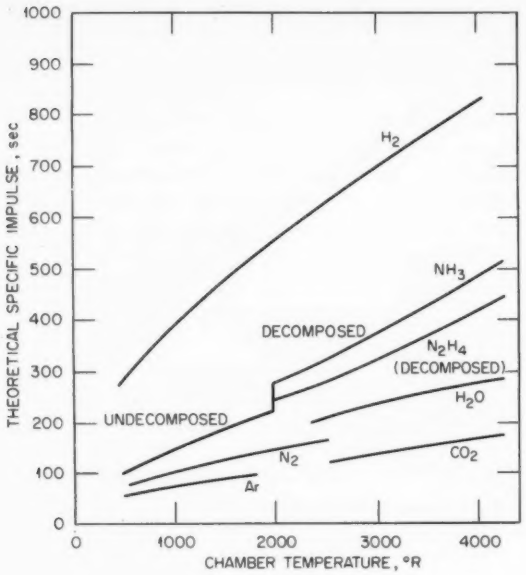

Fig. 3 Theoretical performance of propellants of interest.

¼-lb-thrust units; would require 5 kw(t) of ^{210}Po—chosen for its high power density and suitable half-life; would thrust continuously for periods of about 30 days; and would be clustered to provide thrust levels up to a few pounds. The vehicle typically would weigh less than 10,000 lb, most of which would be the liquid-hydrogen propellant and the payload, and would be useful as the last stage of a deep-space probe, or to raise small payloads from a low earth orbit to a high earth orbit, or similar operations. NASA is examining the capabilities of this type of stage for possible application to its future space missions.

Auxiliary Propulsion Applications. Once launched into space, most spacecraft still require small auxiliary propulsion systems to correct injection errors, to assist in control of the attitude of the spacecraft, to cancel drag, and to maneuver.

Cold gas systems—and to a limited extent subliming solids—with specific impulse in the range of 70 to 100 sec have been used for service in low-thrust, low-total-impulse missions. Monopropellant and bipropellant liquid-fueled chemical rockets (200 to 350 sec) and solid-fueled chemical rockets (200 to 300 sec) have been used for applications requiring higher thrust and higher total impulse. Higher-performance low-thrust propulsion systems at micropounds to a few-tenths-of-a-pound thrust levels are under development and have in a few cases been used in flight. These are primarily electrical propulsion systems of the ion, colloidal, or resistojet type. All these nonnuclear systems require an external source of electrical energy.

Radioisotope-heated thrusters would combine the simplicity, flexibility, and performance of the resistojet with the advantage of requiring no external electric power (except for certain control functions like valve operation). The selection of propellant for a particular application depends on many spacecraft and integration variables. The specific impulse data of Fig. 3 are, of course, one primary factor to be considered. Nitrogen, argon, waste carbon dioxide and water, hydrazine, and hydrogen all offer certain advantages; but, from the standpoint of storage volume, storability, and performance, ammonia is perhaps the best choice for modest total-impulse missions.

A combination of the ammonia-feed-system technology that is under development for the resistojet program and the near-at-hand 2000°F radioisotope-heated capsule temperature capabilities will provide a simple, multinozzle, auxiliary propulsion system with specific impulse in the range of 200 to 250 sec, thrust in the 1- to 100-millipound range, and lifetimes in the range of years, which could be developed for flight in about 3 years.

Objectives

Objectives in the isotope thruster program for primary and auxiliary space propulsion are as follows:

1. To provide a sound technological base for development and for comparison with alternative concepts.
2. To develop radioisotope thrusters as required for use by NASA and DOD.

Program Plan

Primary Propulsion Systems. The primary propulsion thruster[24] requires the use of hydrogen as a propellant, capsule temperatures greater than 3650°F, radioisotope thermal power in the range of 5 kw(t), and a thrust level of about ¼ lb. Following the cooperative Air Force–AEC limited ground test of this class of thruster in February 1965, the AEC continued programs aimed primarily at establishing the radioisotope fuel form and capsule technology necessary for service at this temperature. In the current program, work on 3650°F capsule technology is being emphasized. A large part of the technology required for this heat source is being developed under the fuels development program described under Space Power Systems.

Auxiliary Propulsion Systems. The Commission has conducted two programs (with NASA and the Air Force) over the past 2 years which include ground tests of radioisotope-fueled thrusters.

The unit developed with NASA's Goddard Center is a single-nozzle thruster, built of superalloys, fueled with 60 watts of Pm_2O_3, and designed to produce 20-millipound pulses of a few seconds' duration, at a duty cycle of about 5%. In a series of thruster performance tests at Mound Laboratory in 1966, at 1600 to 1750°F no-flow temperature, thruster performance was good (232 sec peak specific impulse measured). The thruster ground testing is completed. Capsule posttest examination is scheduled for FY 1969.

The Air Force unit is a multiple-nozzle thruster built of refractory metals, fueled with 155 watts of PuO_2, and designed to produce 10 millipounds of continuous thrust and up to 100 millipounds of thrust during low-duty-cycle, pulse-mode operation. This thruster achieved excellent thermal performance (no-flow temperatures of 2080°F compared to 2000°F design temperature). A leak developed in a brazed joint between the propellant flow tubes and the nozzle. The Air Force initiated a follow-on program to redesign, reassemble, and retest this thruster in 1968.

As with all radioisotope systems, a key problem is to assure safe operation and fuel disposal. Toward this end, AEC safety studies of these thrusters are supported by the work in isotope safety described under Space Power Systems. (PSB)

References*

1. AEC Report on Systems for Nuclear Auxiliary Power (SNAP), *Isotop. Radiat. Technol.*, 1(4): 325-339 (Summer 1964).
2. M. P. Norin, SNAP-19 Power System for Nimbus-B, in *Radioisotopes in Aerospace*, Part 2, pp. 427-436, Plenum Press, New York, 1966.
3. F. Schulman, Isotopes and Isotope Thermoelectric Generators, in Report NASA-SP-131, pp. 73-93, National Aeronautics and Space Administration, 1966.
4. A. J. Clark, Jr., New Developments in the Space Isotope Power Program [from 5th Space Congress, Cocoa Beach, Fla.], USAEC Report SC-DC-67-2119 (CONF-680301-1), Sandia Corp., December 1967.
5. *a.* J. E. Boretz, Isotope Dynamic Space Power Systems, American Society of Mechanical Engineers, in *Advances in Energy Conversion Engineering*, pp. 615-651, New York, 1967.
   b. D. W. Linde, 250-Watt Radioisotope Thermoelectric Power Supply System, in *Advances in Energy Conversion Engineering*, pp. 197-206, American Society of Mechanical Engineers, New York, 1967.
   c. Savannah River Laboratory, Large Scale Production and Applications of Radioisotopes, Proceedings of the American Nuclear Society National Topical Meeting, March 21–23, 1966, Augusta, Ga., USAEC Report DP-1066 (Vols. I and II) (CONF-660305), May 1966.
6. G. A. Fowler, Aerospace Safety of Isotopic and Reactor Power Sources, in *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1964*, Vol. 13, p. 146, United Nations, New York, 1965; abridged version; *Isotop. Radiat. Technol.*, 2(4): 350-355 (Summer 1965).
7. Radioisotopes: Production and Development of Large-Scale Uses, *Isotop. Radiat. Technol.*, 6(2): 138-144 (Winter 1968–1969).
8. E. J. Hennelly and R. Hood, Radioisotope Production Capabilities of U. S. Power Reactors, USAEC Report DP-1015, p. 13, Savannah River Laboratory, November 1965.
9. Large Scale Production and Applications of Radioisotopes, *Isotop. Radiat. Technol.*, 4(2): 160 (Winter 1966–1967).
10. Sanders Nuclear To Study ^{170}Tm, *Isotop. Radiat. Technol.*, 5(4): 347 (Summer 1968).
11. Isotopic Power Development, *Isotop. Radiat. Technol.*, 4(2): 174 (Winter 1966–1967).
12. J. R. Wetch and M. G. Coombs, Nuclear Reactor Space Power Systems, Preprint Paper No. CP62-1203, American Institute of Electrical Engineers, New York, 1962.
13. R. E. Niggemann, Organic Rankine Cycle Technology Program, USAEC Report SAN-651-65, Aviation Division, Sundstrand Corp., July 15, 1968.
14. J. E. Carden, Isotopic Power Development, *Isotop. Radiat. Technol.*, 4(2): 177-180 (Winter 1966–1967).
15. J. E. Carden, Isotopic Power Development, *Isotop. Radiat. Technol.*, 4(2): 180 (Winter 1966–1967).
16. W. H. Pennington, D. W. Cole, and W. E. Mott, Radioisotopic Power Sources for Human Implantation, *Isotop. Radiat. Technol.*, 5(4): 306 (Summer 1968).
17. *a.* Thermal Applications, *Isotop. Radiat. Technol.*, 5(1): 64-65 (Fall 1967).
    b. W. H. Pennington, D. W. Cole, and W. E. Mott, Implantable Radioisotope-Powered Circulatory Support Systems, *Isotop. Radiat. Technol.*, 5(4): 307-312 (Summer 1968).
18. *a.* C. A. Metzger, A. B. Hearld, B. J. Reynolds, R. Shivers, and R. W. Murray, Integrated Waste-Management System with a Vacuum Distillation–Vapor Pyrolysis Radioisotope-Fueled Water-Reclamation Function, *Isotop. Radiat. Technol.*, 5(3): 242-251 (Spring 1968).
    b. R. H. Lafferty and J. E. Carden (Eds.), Division of Isotopes Development Research and Development Projects, 1967, USAEC Report TID-24349 pp. 53-55, May 1968.
19. R. H. Lafferty and J. E. Carden (Eds.), Division of Isotopes Development Research and Development Projects, 1967, USAEC Report TID-24349 pp. 56-57, May 1968.
20. *a.* Design of the World's First Industrial-Scale Grain-Irradia-

*See also references to Part I of this article [*Isotop. Radiat. Technol.*, 6(2): 143-144 (Winter 1968–1969)].

tion Facility, *Isotop. Radiat. Technol.*, 4(4): 396-398; 435 (Summer 1967).

b. The Tour of the Portable Cesium Irradiator, *Isotop. Radiat. Technol.*, 5(4): 289-292 (Summer 1968).

c. Food Irradiation, *Isotop. Radiat. Technol.*, 3(4): 342-349 (Summer 1966).

d. D. M. Yates, G. W. Collings, I. L. Kinne, J. R. Kircher, J. H. Litchfield, and O. Wilhelmy, Jr., The Commercial Prospects for Selected Irradiated Foods, *Isotop. Radiat. Technol.*, 6(1): 77-83 (Fall 1968).

21. *a.* Recent Developments in the Production of Wood–Plastic Combinations, *Isotop. Radiat. Technol.*, 3(2): 115-146 (Winter 1965–1966).

b. R. E. Greene, Sixth Annual Contractors' Meeting on Process Radiation Development, *Isotop. Radiat. Technol.*, 4(3): 264-265 (Spring 1967).

22. *a.* D. E. Harmer, Radiation Processing: Where We Stand Now, *Isotop. Radiat. Technol.*, 4(3): 267 (Spring 1967).

b. D. S. Ballantine, Study of Radiation Processing, *Isotop. Radiat. Technol.*, 6(2): 164-173 (Winter 1968–1969).

c. J. H. O'Donnell, Radiation-Induced Solid-State Polymerization, *Isotop. Radiat. Technol.*, 6(1): 85-93 (Fall 1968).

23. Radiation Processing Applications Development, *Isotop. Radiat. Technol.*, 5(1): 78 (Fall 1967).

24. *a.* R. T. Carpenter, U. S. Atomic Energy Commission Isotopic Power Applications, in USAEC Report DP-1066, Vol. I, p. V-6, Savannah River Laboratory, May 1966.

b. TRW Systems, Radioisotope Applications in Space Program (POODLE), USAEC Report STL-517-0034, Vols. I and II, October 1965.

Section
II
Isotopes and Radiation Technology

Isotope Technology Development

Nuclear Logging Methods*

By Richard L. Caldwell†

Abstract: *New developments in nuclear logging methods with special emphasis on industrial uses are surveyed. The use of natural gamma logs to give rock lithology; gamma-ray scattering to give density information and to locate concentrations of heavy elements in rocks; neutron logs for porosity determination and oil–saltwater differentiation; and combinations of logs to identify lithology and deposits of nonmetallic minerals are discussed. Future nuclear logging techniques for lunar and planetary surface analysis, for ocean-bottom sediment-density gaging, and for photonuclear activation of geologic samples are suggested. Computer methods for the analysis of complex gamma spectrums are also discussed.*

Practically every well drilled in the earth in the search for oil is "logged" with tools lowered into the hole to measure properties of rocks surrounding the hole. Logs provide a fast, detailed, and economical reconnaissance of the entire length of drilled hole. In the past, cores obtained from selected sections in wells have been examined and analyzed in the laboratory to guide interpretation of the field logs. Now nuclear logging methods are being widely used in the petroleum industry and are beginning to be used to find and evaluate other commercially important minerals.

Nuclear well logging was introduced on a commercial scale in the petroleum industry about 1940 for identifying different types of rocks and estimating the porosity of reservoir rocks. Most of the early nuclear well-logging techniques were developed on the basis of empirical results obtained from boreholes. During the past 10 years, there have been a number of research programs on investigating the fundamental processes occurring when nuclear radiations impinge on common earth elements, sedimentary rocks, and the fluids found in these rocks and in the boreholes.[1,2] As a result of these basic investigations carried out in a number of different countries, several major advances in nuclear logging have taken place. The primary purpose of this article is to describe these new developments and to give special emphasis to the methods which industry is finding most useful. A secondary purpose is to show the direction of current research and to indicate some of the new types of nuclear logs that we might expect in the future. Table 1 gives a summary of nuclear logging methods.

Some of the possibilities for future nuclear logging techniques are lunar and planetary surface analysis, ocean-bottom sediment-density determination, photonuclear activation of geologic samples, and computer application to the analysis of complex gamma-ray spectrums.

Natural Radioactivity

Measurement of the natural radioactivity of rocks by use of the familiar gamma-ray log gives a qualitative indicator of rock lithology. Normally high counting rates designate shales or volcanic ash, while low counting rates are found at anhydrite, salt, coal, limestone, dolomite, or sandstone deposits. However, some sand formations may either be radioactive or contain radioactive waters and thus can be confused with shale. Gamma-ray logging is also an excellent means of prospecting for economically valuable deposits of both uranium and potash (K_2CO_3).

Numerous measurements of the natural radioactivity of rocks have been made in a number of different laboratories,[3-5] and the relation of the

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Table 1 Nuclear Logging Methods

Type of log	Purpose	Current status
Natural gamma ray	Lithology identification	Commercial
Gamma-ray scattering	Rock density (porosity)	Commercial
	Cement behind pipe	Commercial
	Minerals location (high-atomic-number elements)	In development
Neutron		
Steady-state methods		
Thermal neutron, gamma	Porosity (and salinity)	Commercial
Epithermal	Porosity	Commercial
Long spacing	Porosity	In development
Pulsed method	Oil–saltwater differentiation	Commercial
Gamma-ray spectrum	Chlorine	Commercial
	Element identification	In development
Combinations of logs (density, neutron, acoustic)	Lithology identification	Commercial
	Evaluation of nonmetallic mineral deposits	Commercial

uranium, thorium, and potassium contents to that of clay in rocks, particularly carbonates, has been investigated in detail. The natural radioactivity of the rock walls of a borehole has been measured experimentally by spectral analysis using a sodium iodide scintillation crystal detector. However, neither the laboratory studies nor the field experiments have resulted in new practical logging procedures. Today there is no routinely used commercial service for obtaining spectral analysis of natural radioactivity.

In the United States the principal advancement in recent years in natural gamma-ray logging has been the establishment by the American Petroleum Institute of primary standard test wells for the calibration of gamma-ray logging equipment made by various companies. These artificial formations contain known quantities of K, U, Ra, and Th in amounts representative of average sedimentary formations. Gamma-ray logs can now be compared quantitatively even though made with equipment from different companies and under different borehole conditions.

Gamma-Ray Scattering

Logging based on the scattering and absorption of gamma rays is usually referred to as "gamma–gamma" logging. Techniques have been developed for measuring rock density, for evaluating cement distribution around the borehole pipe casing, and for obtaining the average concentration of heavy elements in rocks in the exploration for solid minerals.[6] The relation between source energy, source–detector spacing, rock density, chemical composition, and energy of detected radiation determines the response of the gamma–gamma probe.

For measuring the density of rocks or of cement around a pipe, an intermediate-energy gamma-ray source is used. For the energy range 0.5 to 2.0 Mev, Compton scattering is the most important process in the scattering and absorption of gamma rays. By using a collimated source of gamma rays and a collimated scintillation crystal detector, narrow-beam geometry (for which exponential absorption applies) can be approximated in a practical logging tool. For location of solid minerals, the large photoelectric absorption of low-energy radiation by elements of high atomic number is utilized. Energies less than 0.15 Mev become important in this application.

Formation-Density Logging

Although formation-density logging has been in use for more than 10 years, the method has become widely accepted only since the recent introduction of the dual-spacing modification. In the older density logging systems using a single detector, the response is seriously affected by mudcake and borehole irregularities. A new compensated formation-density logging device uses two detectors spaced at different distances from the source.[7]

The detector at the shorter spacing is particularly sensitive to the density of material immediately adjacent to the face of the probe. The contribution of this material, which includes that from mudcake and minor wall irregularities, affects the response of each detector

to a different degree. The signals from both detectors are combined to give automatically a density correction that is incorporated in the uncompensated density information from the detector at the longer spacing. Both the compensated density measurement (ρ_b) and the amount of compensation ($\Delta\rho$) are recorded on the log (Fig. 1).

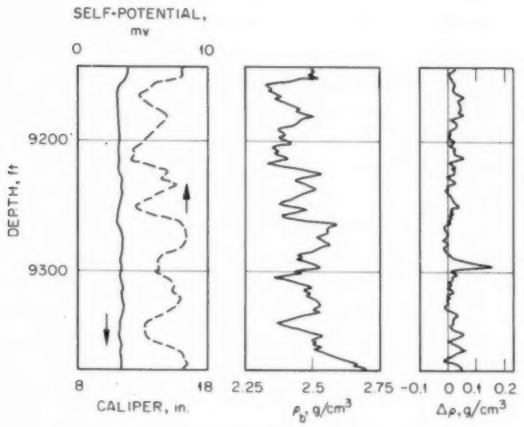

Fig. 1 Formation-density log, compensated. Mud weight, 10.6 lb/gal; ρ_b = compensated bulk density; $\Delta\rho$ = amount of compensation.

The $\Delta\rho$ curve, which shows how much density compensation had to be applied to obtain the corrected bulk density, ρ_b, is useful as a sensitive indicator of mudcake and irregularities of the borehole. The compensated bulk-density curve is scaled linearly in grams per cubic centimeter, thus removing the need for point-by-point conversion of standard counts per second to bulk density. Usually a caliper trace is also recorded on the log to show variations in borehole diameter. Prior knowledge of mudcake density and thickness is not required in the determination of $\Delta\rho$ and the correction of ρ_b. If mudcake thickness does not exceed 0.5 in., the error in the computed $\Delta\rho$ is small compared to the magnitude of the compensations. For cases where sizable $\Delta\rho$ values are indicated on the log, the information given in Ref. 7 can be used to determine the compensation error and thus further correct the recorded value of ρ_b.

Tool (probe) calibration is based on readings in laboratory limestone formations of high purity and accurately known densities. Precision aluminum blocks that have been related to the limestone formations are used as secondary standards when the tool is taken into the field. The tool is designed to operate at a pressure of 20,000 psi and a temperature of 350°F. Maximum recommended logging speed is 1800 ft/hr. The minimum recommended borehole diameter is 5 in.

Density logs are also excellent for identification of coal. The low densities of coals—from 1.4 to 1.8 g/cm³ for anthracite, 1.2 to 1.5 g/cm³ for bituminous, and 0.7 to 1.5 g/cm³ for lignite—cause distinctive log deviations. The density log also provides information on the quality of coal. The ash content of coal, which depends on the quantity of included mineral impurities, such as silica, alumina, and iron oxide, is an important factor in determining its commercial value. Because all mineral impurities of significance have appreciably higher densities than the carbon and hydrocarbons of coal, a density log provides an estimation of the variations in ash content for any given coal seam. The ash content is related very nearly linearly to specific gravity or density within a given coal seam.

Cement Surrounding Pipe Casing

Scattered gamma-ray logging for cement evaluation is in common use in the USSR and to a much lesser extent in the United States. The tool in current use in the Soviet Union has a single gamma-ray source and three gamma-ray detectors, equally spaced around the axis of the tool. Lead shielding between the source and detector prevents direct transmission of gamma rays. Centralizers at the top and bottom keep the tool centered in the borehole. This type of tool, with three detectors, has been in use since 1960.

Figure 2 is an example of one of these three-trace logs, which is called a "cementogram"; also shown in the figure is a caliper log of the hole. Interpretation of the three-trace logs is complex but is aided by laboratory results in which various cementing conditions were "logged" using a steel pipe and cement rings of various sizes. When the three curves can be more or less superimposed, it is concluded that the cement is uniform around the pipe. Divergence of one or more of the curves indicates irregular cementing or channeling. The model results also help to interpret logs obtained when the pipe is not centered in the hole.

Metallic Minerals Logging

There has been some work, particularly in the Soviet Union, on the determination of heavy elements in rocks and ores based on the selective photoelectric absorption of low-energy gamma rays by high-atomic-

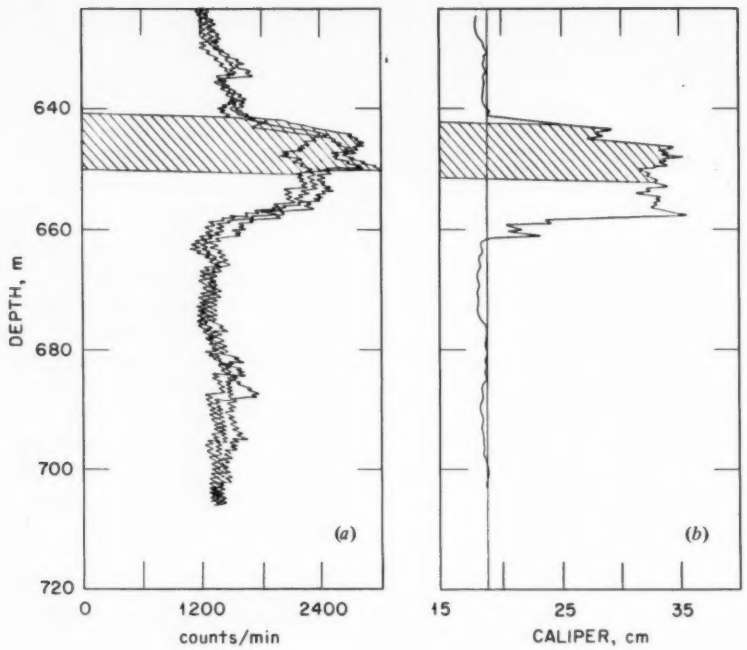

Fig. 2 (*a*) Cementogram and (*b*) caliper log. The shaded area indicates irregular cementing or channeling.

number elements. The determination of heavy elements in rocks and ores gives best results when the ore and surrounding rocks have practically the same density and when the rock matrix is composed of elements with low atomic number. This technique gives the average concentrations of heavy elements in rocks. A comprehensive theoretical analysis of this technique, referred to as "selective gamma–gamma" logging, has been made by Czubek[8] in Poland. He also compares theoretical predictions with experimental results and shows how to obtain the optimum design of a selective gamma–gamma tool. The method should be particularly useful for determining mercury, lead, and tungsten.

Neutron Methods

Steady-State Methods

Neutron logging can be classified according to the type of source—steady-state or pulsed-neutron—used and the type of radiation detected. The conventional methods in use since 1940 all employ a steady-state source (a mixture of Ra, Po, Pu, or Am with Be metal) and a detector of either thermal neutrons or capture-gamma rays. Only very recently have truly epithermal-neutron detectors been used, and a recent theoretical paper[9] from our laboratory shows that at very long spacings an epithermal-neutron response can be achieved using thermal-neutron detectors.

Thermal-Neutron–Gamma Logs. All logs made using steady-state neutron sources and conventional detectors of thermal neutrons or capture-gamma rays show a response to a combination of porosity (hydrogen content) and salinity (chlorine content). Logs are run in both open and cased holes and for many years have been widely used, particularly in low-porosity carbonate rocks. Various service companies have published literature on the design, calibration, and performance of their respective tools, which are all sensitive to changes in the borehole parameters and are unable to separate the responses to porosity and salinity. Nevertheless, these are today the only logging tools used routinely for obtaining porosity in cased holes.

Sidewall Epithermal-Neutron Porosity Log. A new sidewall neutron porosity (SNP)-logging system, developed for use in uncased wells,[10] substantially reduces

environmental effects that have previously complicated neutron-log interpretation. The effects of variations in borehole diameter, fluid salinity, mud weight, and temperature are suppressed or corrected for by this new system. Small residual borehole effects are then computationally accounted for in the surface control panel to provide a borehole-corrected neutron log. The log is a direct record of neutron-derived porosity on a linear scale. With corrections from borehole effects already applied, this direct recording of porosity simplifies log interpretation.

The improvements in performance arise primarily from two important design features. First, the neutron-detection system is mounted in a directionally sensitive sidewall skid to greatly minimize borehole effects. Second, although not unique to this new tool, an epithermal-neutron-detection system is used.

Epithermal-neutron detection, of all the neutron methods in current commercial use, provides the simplest determination of formation-hydrogen content. Hydrogen plays a very important role in the process of slowing down fast neutrons to epithermal energies; and the flux of epithermal neutrons is therefore determined primarily by hydrogen content. The absorption effects related to water salinity and to low concentrations of other strong thermal-neutron absorbers are very important in neutron diffusion and capture, and in the production of gamma rays. However, these absorption effects are relatively unimportant in the process of moderating neutrons from high to epithermal energy levels. Thus, by detecting only epithermal neutrons, the perturbing influences of thermal absorption by the rock matrix and salts in the water are minimized as compared to other tools using thermal-neutron or gamma-ray detectors.

The advantages of epithermal-neutron detection have long been known but have been applied only recently, as a result of a major advancement in instrumentation. Most epithermal-neutron detectors of the past have suffered from low epithermal detection efficiency and high sensitivity to gamma rays. The new SNP tool incorporates a new type of detector that does not have these disadvantages. With a high-efficiency detector, normal logging speeds are practical while counting rates are good.

The down-hole part of the SNP equipment is similar to that of the dual-spacing density tool. The epithermal-neutron detector and the Pu–Be or Am–Be neutron source are in a sidewall pad that is pressed firmly against the borehole wall. This design enables the directional detection system to count neutrons arriving primarily from the formation rather than those coming from the borehole fluid. The influences of both borehole and mud properties are thereby reduced.

The porosity response of the tool was obtained by calibration in a variety of laboratory formations of accurately known matrix composition and porosity. The results of these measurements describe the response in both water-filled and empty holes for quartz, sand, limestone, and dolomite matrixes.

Figure 3 shows an SNP log made in carbonate rock, together with gamma-ray, caliper, and density logs. The SNP log shows the effectiveness of the system in overcoming the effects of hole-size variations. The log was recorded through an evaporite sequence in a well in west Texas. The salt beds were identified by low density values (approximately 2.10 g/cm^3), and the boreholes are shown by the caliper to be washed out to diameters as large as 15 in. The high-density zones are predominantly anhydrite but include some dolomite stringers. Throughout the salt beds, the SNP correctly indicates apparent porosity values of approximately

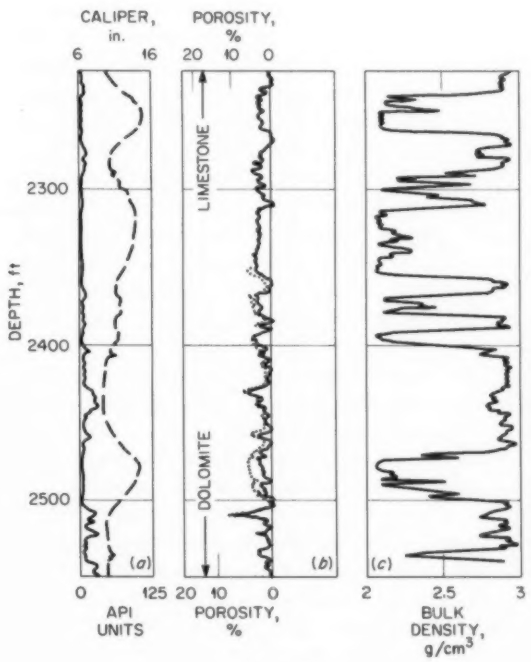

Fig. 3 Sidewall neutron porosity (SNP) log recorded in liquid-filled hole through evaporite section showing (*a*) gamma log (solid line) and caliper log (dotted line); (*b*) porosity (dotted line is repeat run without caliper signal compensation); and (*c*) bulk density (formation density log, compensated).

4%. The very dense anhydrite zones present apparent porosities slightly less than zero. The dotted curve superimposed on the SNP is the repeat run of this log, during which no caliper signal compensation was applied. Although the amount of correction is significant in the very-large-diameter sections, it is much smaller than would be required for other neutron logging systems.

Long Spacing Log. A frequent criticism of neutron-logging methods in the past has been that they are too sensitive to borehole size, type of fluid in the borehole, and position of the logging instrument in the borehole. We have seen that the sidewall epithermal-neutron log for use in uncased holes overcomes, to a considerable degree, many of these difficulties. An improved neutron log for use in cased holes would be very beneficial for logging the tens of thousands of wells on which we do not have good porosity information, particularly on formations above the zone to which the well was originally drilled for oil production.

It is known that, on a relative basis, the strong attenuator for both epithermal and thermal neutrons is the liquid-filled borehole, and the weak attenuator is the formation. Thus, for increased sensitivity to the properties of the formation, the detector should be positioned as far from the source as possible, allowing neutrons that travel toward the detector within the borehole to be attenuated relative to those traveling in the proper direction within the formation.

Until recently it has not been possible to capitalize on this benefit of large source–detector spacings because the necessary high-efficiency detectors and high-yield neutron sources were not available. However, high-pressure proportional counters filled with ^{3}He and high-yield Po–Be neutron sources are now marketed. It should therefore be possible to realize any advantages that may accrue to logging instruments employing large source–detector spacings.

Recently, theoretical studies have been made using one- and two-group neutron-diffusion theories to explore the possibilities of such instruments.[9] The results show that the ratio of thermal-neutron fluxes at two appropriately large distances along the axis is virtually identical to the epithermal-flux ratio and is a measure of a single epithermal parameter of the formation—i.e., the slowing-down length. It is well known that the slowing-down length is strongly dependent on hydrogen content. The theoretical studies also showed that variations in salinity of the liquid in the formation or in the borehole and changes in borehole size have relatively little effect on the flux ratio. The results of experiments using a borehole model to study the effects of tool position in the borehole showed that the ratio of thermal-neutron counting rates at large distances from the source is not seriously affected by the position of the logging instrument in the borehole. Studies also showed that reasonable changes in borehole diameter have only a small effect on the porosity as indicated by the ratio measurement.

Since the thermal-neutron flux ratio is affected very little by borehole size and not at all by the position of the logging instrument in the borehole, it is reasonable to conclude that the ratio will not be much influenced by the presence of an iron casing and cement. These studies suggest that the porosity log can be improved by use of 70- and 90-cm source–detector spacings with a neutron source of 5×10^8 n/sec or greater. This tool is not commercially available, but the studies show that it should be a distinct improvement for logging of both cased and open holes.

Pulsed Method

Much work has been done in recent years in the United States and in the Soviet Union on the use of a pulsed source of 14-Mev neutrons to improve the logging method for differentiation of oil and salt water. Typically, the burst of fast neutrons lasts for 50 μsec, and, after the end of the burst, the "die-away" of thermal neutrons or capture-gamma rays is observed for 1000 to 3000 μsec. The Russians have used thermal-neutron detectors exclusively, while most of the work in the United States has been with scintillation crystals to detect gamma rays arising from the capture of thermal neutrons.

Figure 4 shows typical neutron-lifetime curves for oil and saltwater saturation of a 20% porosity sandstone formation. Typically, the slope of the curve is determined by using two time windows. The asymptotic portions of the curves are independent of whether neutron or gamma-ray detection is used. It is obvious that at later times there is better spread between the two curves.

Figure 5 shows why this log is useful. The resistivity log was made in an open hole when the well was originally drilled, and the neutron-lifetime log in the cased hole. The die-away curve reads like a resistivity curve, with low readings opposite saltwater-saturated zones and high readings opposite oil saturation. For the first time we have a nuclear log for use in cased holes with a sensitivity for oil–saltwater differentiation approaching that of the open-hole electrical resistivity log.

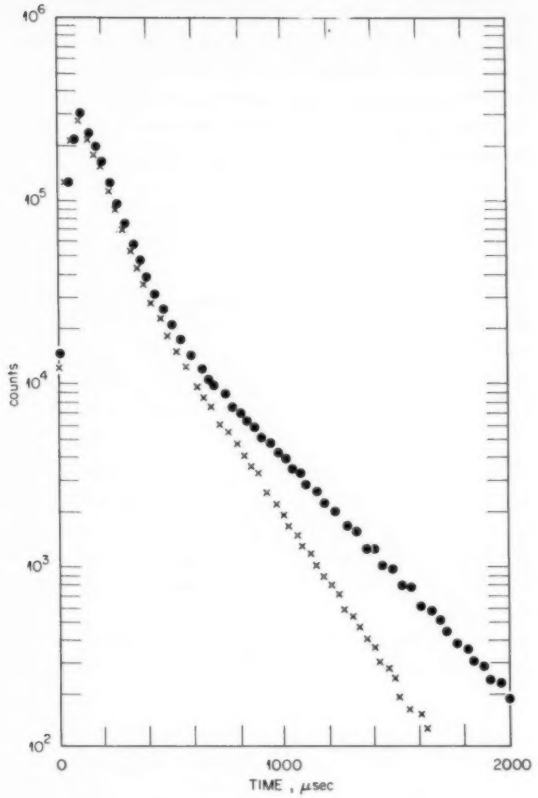

Fig. 4 Typical neutron-lifetime curve for oil (•) and salt water (X). Asymptotic lifetime from computed least-squares fit of two curves: 330 μsec for oil and 245 μsec for salt water.

At the 1967 Well Logging Society Symposium, a large-scale application of the neutron-lifetime log was described for operations of the British Petroleum Company Ltd. in the Middle East.[11] After development of a field, one of the constant aims is to produce reserves more efficiently and, hence, more cheaply. Unexpected water from individual wells proved to be a costly production problem. This was partially solved by routine fieldwide checks of the position of the oil–water contact, using first a through-tubing chlorine-logging tool. The results showed that regular monitoring of the rise in oil–water contact over a producing field gave invaluable data for more efficient production and reservoir control. Subsequent logging runs were made with the new neutron-lifetime tool. Use of these logs enables the reservoir engineer to draw contour maps of present oil–water contacts. As a result of such information, production rates can be varied to give more efficient overall reservoir control.

Small-diameter neutron-lifetime tools for running through tubing have been developed[12] with outside diameters of $1\frac{11}{16}$ and $2\frac{1}{8}$ in. The tools should be useful not only for detecting fluid level but also for indicating the direction of fluid flow outside the casing by means of neutron activation. The tools have potential application for logging through drill pipes where it is impossible or impractical to pull the pipe in order to run open-hole logs. This may be the case in some offshore exploratory wells where no wellhead equipment is used or where the pipe is stuck. The new, slim, neutron-lifetime logging tools are available on a limited basis from the Dresser Atlas Division of Dresser Industries, Inc., and Schlumberger Well Services, Division of Schlumberger Technology Corporation. The tools can be used in $3\frac{1}{2}$-in. drill pipe or in 2- or $2\frac{1}{2}$-in. tubing. Logging speed is about 10 ft/min, and a gamma-ray log can be run simultaneously. The results from logs that have been obtained with these tools are encouraging.

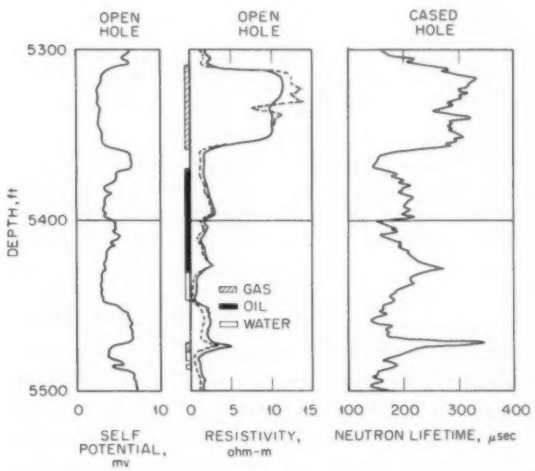

Fig. 5 Gulf coast open-hole and cased-hole logs.

Combinations of Logs

The available variety of logs enables measurement of many parameters useful in mineral identification. More than 10 years ago, workers in Poland showed that combinations of nuclear well logs could be used for identifying various rock lithologies and for distinguishing the minerals sylvite, carnallite, halite, and kieserite.

Measurements were made of the natural beta and gamma radioactivities, as well as of scattered gamma radiation (gamma–gamma method) and of neutron-induced gamma radiation (neutron–gamma method). The measurements were made in a salt mine in horizontal boreholes. Potassium salts were recognized by their high natural radioactivity due to ^{40}K, and the potassium minerals, sylvite and carnallite, were distinguished from each other on the basis of the neutron log since carnallite contains water of crystallization. Hydrogen is a good neutron moderator, so that the neutron reading is lower opposite carnallite.

Lithology evaluation by a combination of logs has recently been used successfully in oil wells, and, within the past 2 years, combinations of logs have been shown to be equally useful for nonmetallic, solid minerals evaluation.

Lithology Identification

In 1963 several papers were published on the determination of mineral composition in a complex lithology by use of sonic, neutron, and density logs. These logs have been used to evaluate oil shale. In zones of high oil yield, both sonic and density logs indicate increases in the apparent porosity. The density log appears to give greater resolution and hence better predictions of the potential yield of oil from the shale.[13]

When the lithology is known, rock porosity may be read directly from either the sidewall epithermal-neutron log or the density log and seldom requires further correction. When the lithology is not accurately known, which is often the case, porosity errors can result from an incorrect assumption of the nature of the matrix. By comparing the apparent limestone porosities read from the neutron and density logs, it is possible to obtain an improved value of porosity and, at the same time, to identify the matrix lithology. Reference 10 describes a crossplotting technique for comparison of porosities derived from the two logs. On such a crossplot, anhydrite, dolomite, limestone, and quartz sand all fall along different lines. When the actual formation matrix is a single rock type, the position of the line identifies the lithology and indicates the true porosity. If the matrix is known to be a mixture of two of the rock minerals shown, the plot, by interpolation, provides their relative approximate fractions in the mixture and also indicates the correct porosity.

In field practice, few formations are found to have a matrix composed of a single rock mineral. Most are mixtures or contain impurities. This is illustrated in Fig. 6 by plots of data taken from 25 wells in various areas thought to be relatively pure sandstones and dolomites. Although some scatter is apparent for the dolomite points, there is a clear division of the points along two lines, indicating two lithologies.

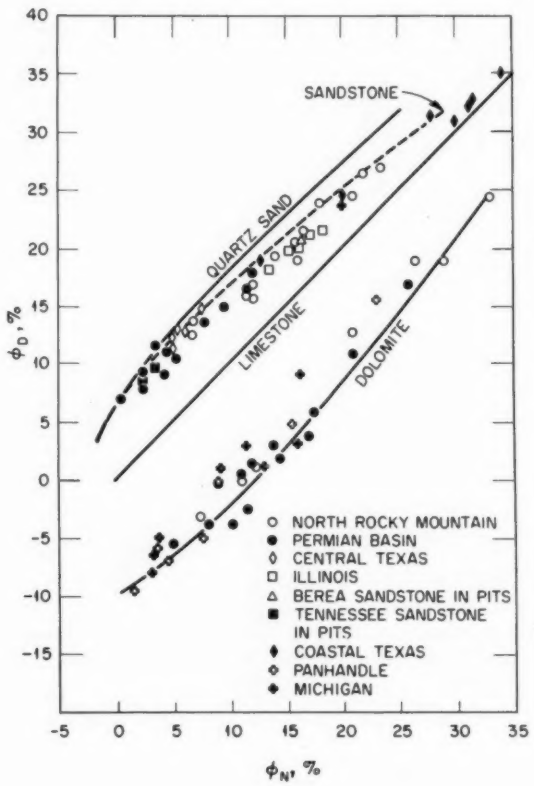

Fig. 6 Crossplot comparisons of apparent limestone porosities of sandstone and dolomite formations from neutron- and density-log data. ϕ_N is apparent limestone porosity determined from neutron-log data. ϕ_D is apparent limestone porosity determined from density (gamma)-log data.

Log Evaluation of Nonmetallic Mineral Deposits

Tixier and Alger[14] have recently described the use of well logs to locate and evaluate deposits of various commercially important minerals. For evaluation it is necessary only that the mineral of interest represent a significant fraction of the formation bulk volume and that it exhibit characterizing properties measurable by logs.

For evaluation of sulfur deposits, either gamma–gamma density or sonic logs provide good resolution when compared with porosity computed from neutron or resistivity logs. Large differences between the density and neutron logs indicate a rich sulfur content.

Logging techniques are well suited for locating and identifying commercial evaporite deposits. Bedded evaporite minerals are essentially nonporous and electrically nonconductive. Thus they are characterized by extremely high readings on resistivity logs. Unless affected by borehole enlargement, resistivities recorded opposite evaporite beds are higher than those obtained in adjacent sedimentary formations. Because some evaporites are quite soluble in water-base drilling fluids, resulting in enlarged holes, use of the caliper log is important.

While resistivity and caliper measurements locate evaporite deposits, they do not identify the particular mineral, but, since evaporite beds have little or no porosity, a single porosity log—sonic, density, or neutron—will usually provide identification. Figure 7 shows how crossplots of sonic- and neutron-log data clearly separate various evaporite minerals. The evaporite beds most commonly encountered are halite (rock salt), anhydrite, and gypsum. With the use of sonic, neutron, and density logs, deposits of these evaporites are readily identified. In exploration for nonmetallic mineral deposits, well-logging methods provide a fast reconnaissance of the entire hole. Log results compare favorably with core assays.

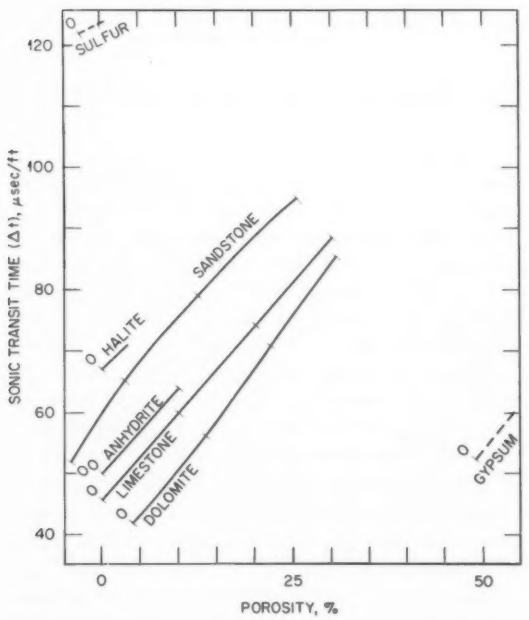

Fig. 7 Crossplot comparisons of sonic- and neutron-log data for mineral identification. Porosity is expressed as percent of apparent limestone porosity.

Nuclear Analysis of Lunar and Planetary Surfaces

The analysis of extraterrestrial surfaces may also be considered a form of logging. One of the objectives of lunar and planetary missions is the remote analysis of the surface at locations where sample collection may be difficult or impossible. Results of these surface analyses can be compared to predictions made from various theories regarding the formation and evolution of the moon and planets. The main question is whether or not the visible lunar features are primarily the result of volcanic activity or of meteorite impact. Knowledge of the moon's surface is also essential for the Apollo manned-landing program.

Nuclear analytical techniques based on the use of neutrons can be used to determine elemental abundances and therefore identify rock types. Estimates of the abundances for the land and "sea" masses of the moon have been made, and the rocks can be classified into three broad categories—acidic, basaltic, and aerolitic. Any one of the three may exist in both the maria and terrae, and a determination of the rock in the two types of regions should provide evidence of either volcanic or meteoritic origin.

Neutron Analysis Techniques and Combination Experiment

Neutron analysis methods utilize the spectral and temporal characteristics of gamma rays produced when neutrons interact with matter. The gamma rays arise from inelastic scattering, capture, and activation. In addition to measuring energies of the three types of gamma rays, one can measure the rate at which the capture-gamma rays die away. The four measurements (inelastic, capture, activation, and die-away) constitute a combination neutron analysis experiment that can be carried out with a single instrument, using a pulsed-neutron source.[15] The data would be telemetered to earth for study.

Figure 8 shows the timing diagram, which is basic to the combination neutron experiment and includes two successive bursts of the pulsed-neutron source. First, inelastic-gamma rays appear promptly and only

during the bursts. Then capture-gamma rays, proportional to the slow- or thermal-neutron density, build up in intensity during each burst and then die away. In the time interval following complete die-away, but before the next burst occurs, activation-gamma rays may be counted cyclically. After the source is turned off, the gamma activity from the induced nuclides decays exponentially.

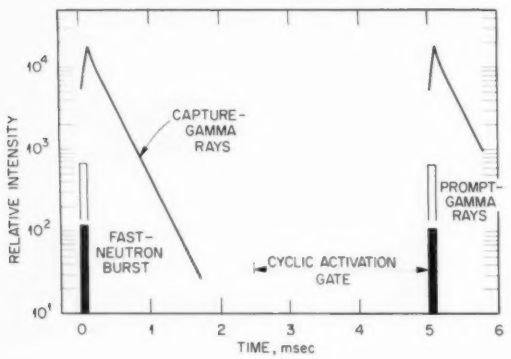

Fig. 8 Timing diagram for combination neutron experiment.

Figure 9 shows idealized gamma-ray spectrums from the five most abundant elements expected in the lunar surface. It can be seen how a qualitative analysis of the elements may be obtained from the spectrums of inelastic-, capture-, and activation-gamma rays. In order to differentiate the three rock types, quantitative results are needed, like those obtained by the ratios of elemental abundances. For example, the O/Si and O/Fe ratios change uniformly across the rock types and provide convenient indicators of specific rock types.

For an actual space mission, the neutron source must be compact, rugged, and reliable. Such requirements can be fulfilled with a miniature accelerator using the deuteron–tritium reaction to produce 14-Mev neutrons. The burst length should be about 5 μsec and the repetition rate about 500 pulses/sec. An attenuator is necessary to shield the detector from the intense burst of X rays and direct fast neutrons from the source during neutron production. The gamma-ray detector will be a high-resolution NaI scintillation counter or possibly a solid-state type.

Our work has been concerned primarily with the die-away rate of capture-gamma rays and the cyclic counting of activation-gamma rays. The die-away rate of capture-gamma rays is governed by that of the neutrons, thus the name "neutron die-away."

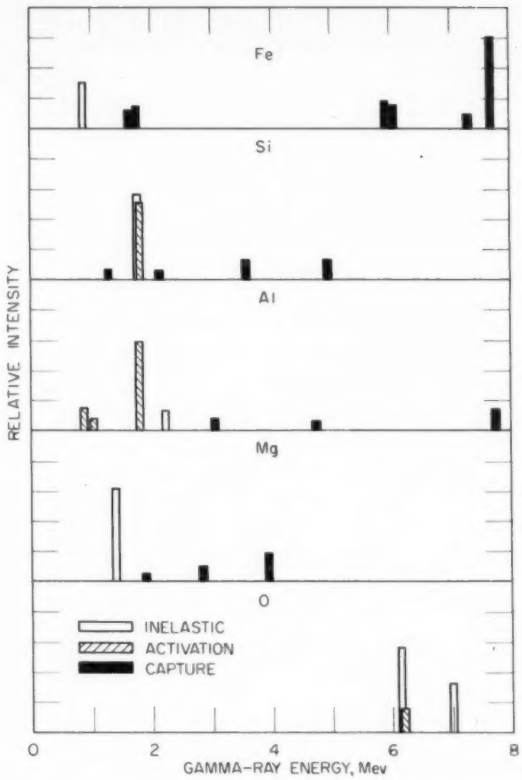

Fig. 9 Spectral diagram for combination neutron experiment.

Several large rock models were used to simulate semi-infinite surfaces of various compositions. These models consisted of a large block of dense granite and three tanks containing crushed granite, basalt, and carbonate rock. Each tank model had a diameter of 9 ft 9 in. and a height of 5 ft 9 in. A moisture seal was provided by enclosing the crushed rock in a sheath of thin polyethylene.

Figure 10 shows some examples of neutron die-away curves obtained on these rock models. Note that granite is represented twice—by two different densities—although the two types of granite are almost identical chemically. The smooth curves are the mathematical best fits to the data points. Figure 11 shows a calibration curve based on the results plotted in Fig. 10. Values along the vertical scale, labeled "rock parameter," were obtained from the known physical and chemical properties of the rocks. Values along the horizontal scale were obtained from the curves in Fig. 10. From the measured die-away rate on an unknown sample, the value of the rock parameter may be read

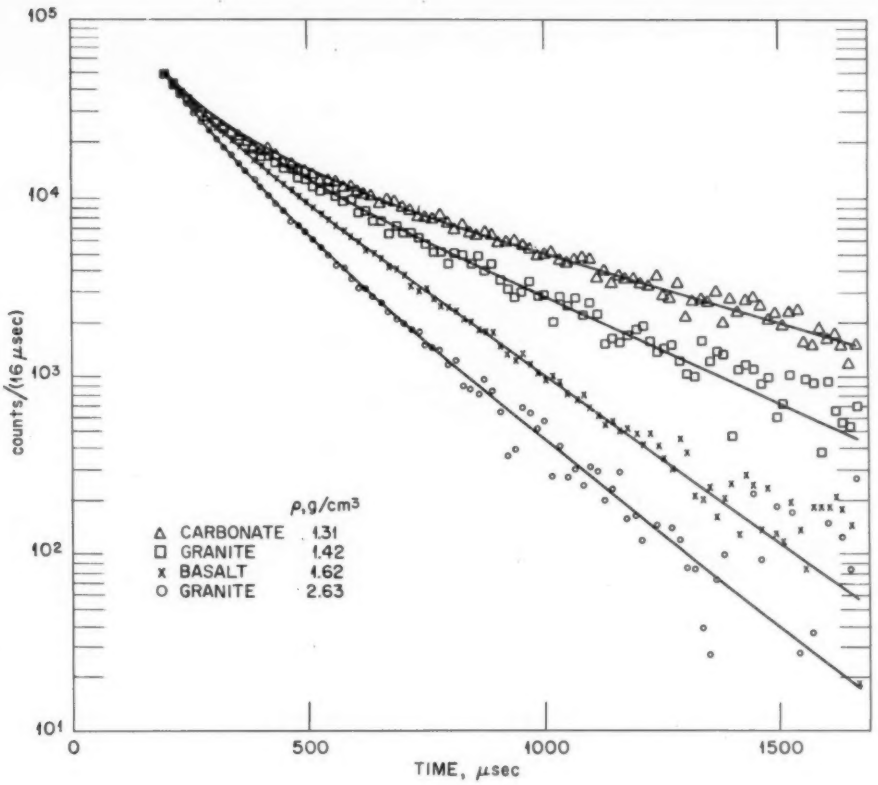

Fig. 10 Neutron die-away curves.

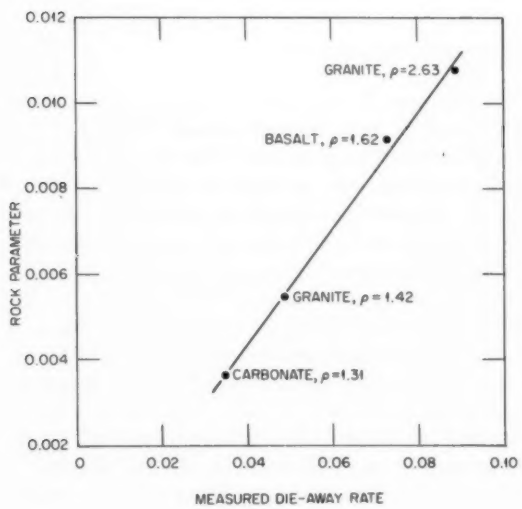

Fig. 11 Calibration for rock parameter.

from the calibration curve. This, in turn, allows one to infer certain information about the unknown sample.

An additional capability of the die-away technique is that hydrogen may be sensed by virtue of its large effect on the neutron slowing-down time, provided that epithermal die-away rates can be measured. Figure 12 shows results obtained with a $\frac{1}{32}$-in. cadmium filter covering a ^{3}He detector. The epithermal die-away rates of the runs shown are consistent with water (hydrogen) concentrations determined from nuclear magnetic resonance measurements and shown in the last column of the table on the figure.

Figure 13 illustrates the ability of the neutron die-away method to detect layering of the rock surface down to depths of about 2 ft. The curves obtained were for layers of crushed granite of various thicknesses overlying dense granite. As the layer thickness increases, the die-away curve changes from that characteristic of dense granite to that characteristic of crushed granite.

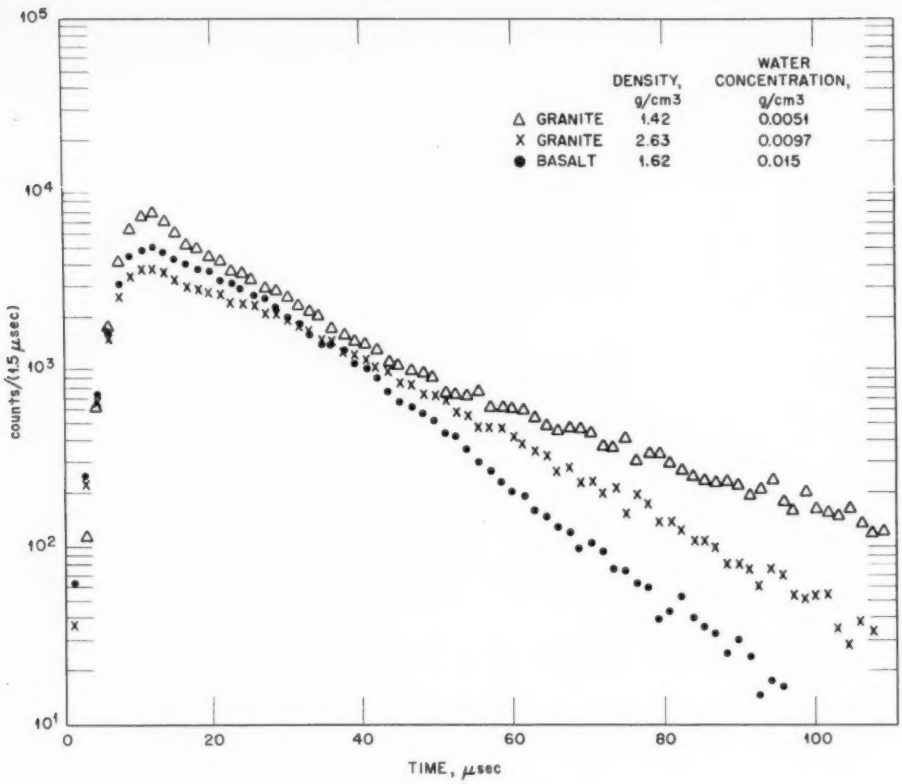

Fig. 12 Epithermal-neutron die-away curves.

As mentioned previously, cyclic counting of activation-gamma rays may be carried out repetitively in the time interval following complete die-away of the capture-gamma rays. This technique is particularly promising for very short-lived activities and, in fact, is the only way to determine half-lives of less than a few seconds. Figure 14 shows cyclic activation results obtained on the granite and basalt models. The timing used was that shown in the timing diagram (Fig. 8). Oxygen and silicon are easily determined by activation with the following reactions: $^{16}O(n,p)^{16}N$ (with a 7.3-sec half-life) and $^{28}Si(n,p)^{28}Al$ (with a 2.3-min half-life), respectively. Figure 14 shows the low-energy portion of the spectrum in which the 2.3-min activity from ^{28}Al [from the (n,p) reaction with silicon] is seen. The peak at 0.473 Mev is produced from both Mg and Al [$^{24}Mg(n,p)^{24m}Na$ and $^{27}Al(n,\alpha)^{24m}Na$] and results in the ^{24m}Na isomer with a 19-msec half-life. Clearly, this activity cannot be utilized in conventional activation techniques.

Computer Methods for Analysis of Complex Gamma-Ray Spectrums

Techniques for geochemical analysis involving measurements of gamma-ray, X-ray, and alpha-particle radiations are being considered for use on lunar and planetary exploration missions. All these require analysis of complex pulse-height spectrums. A frequent application under consideration is the measurement of the characteristics of the pulse-height spectrums of the incident radiation, and from these spectrums the differential energy spectrum must be determined. A linear, weighted least-squares method has been developed to perform this analysis.[16] This technique requires the inversion of a matrix containing a set of standard spectrums to be compared to the pulse-height spectrum. The problem in the use of this technique is to obtain a unique solution. Algorithms for finding such unique solutions consistent with the physical constraints of the problem have been developed.

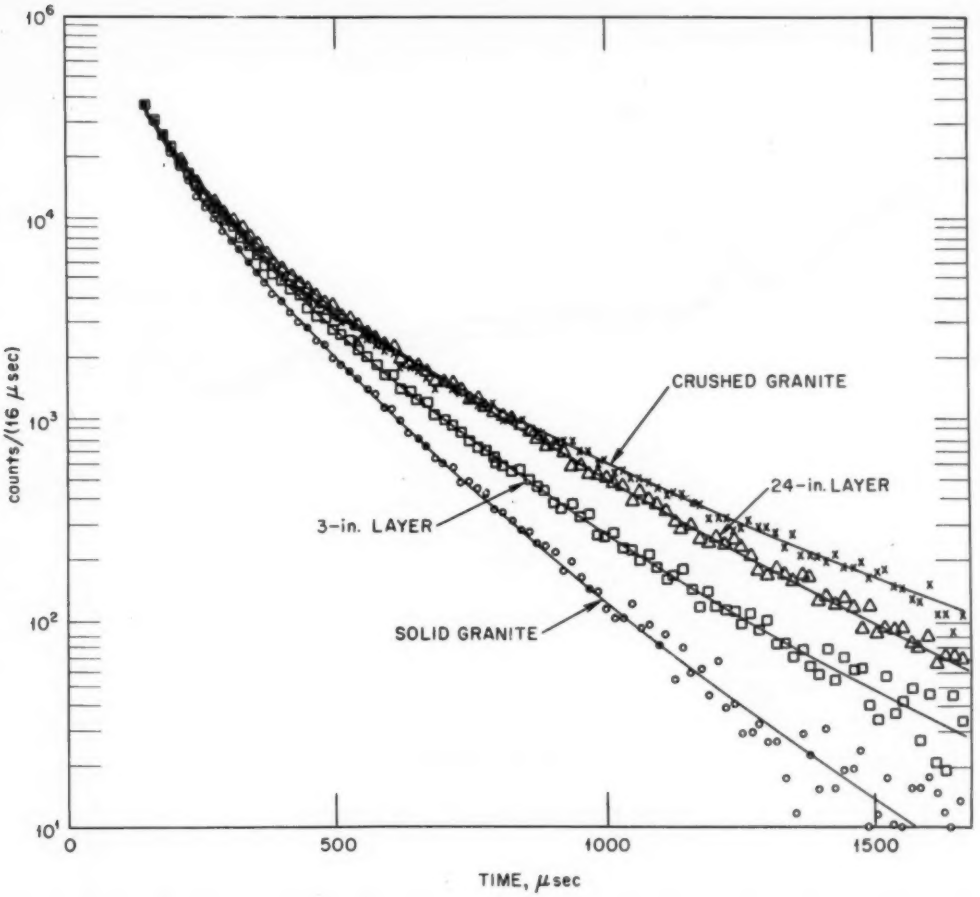

Fig. 13 Neutron die-away on layered model.

Other difficulties in the application of the method to such spectroscopic techniques can be attributed to instrumental gain-shift and zero drift. Instrumental methods for compensating for such changes usually degrade the measured pulse-height spectrums. One approach has been therefore to compensate analytically for these drifts in the least-squares analysis program. This is accomplished by first allowing the program to shift the gain of the measured spectrum (a compression or contraction) and then change the zero level (a linear translation) until the chi-square characteristics of least-squares fit is a minimum. This technique has been used successfully in analyzing a variety of geological rock types by the nondispersive X-ray spectroscopy method. In applications to neutron activation, both qualitative and quantitative determinations have been obtained from analyses of gamma-ray pulse-height spectrums. This is but one example of many computer methods that have been developed.

Photonuclear Activation of Geologic Samples

Photonuclear activation techniques are also of interest to those engaged in nuclear logging and geologic-structure investigations. The scientific literature is replete with studies concerned with thermal-neutron activation analysis of geologic samples but contains relatively few involving photonuclear activation analysis of such samples. A small group at Gulf General Atomic[17] is engaged in an extensive investigation of the potentiality of high-flux photonuclear

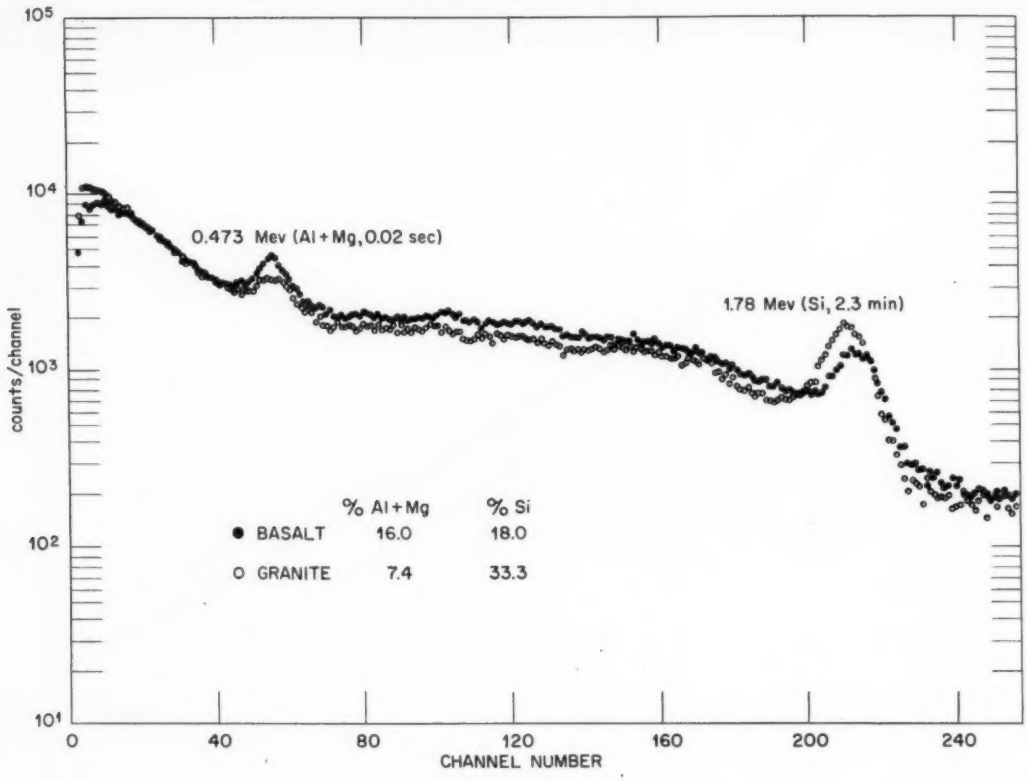

Fig. 14 Cyclic activation gamma-ray spectrums.

activation analysis for the study of samples of many types, including geologic samples. Two high-current linear accelerators, with maximum energies of 17 and 45 Mev, are used. The electron energy of each machine can be varied from about 2 Mev up to the maximum. The diffused electron beam is absorbed in a water-cooled tungsten converter to form an intense bremsstrahlung beam. Samples are irradiated in a high-intensity photon flux, in front of the converter, in either a pneumatic tube or a spinning multiple rack.

Various kinds of samples—pure element, inorganic, mineral, rock, and soil—have been photoactivated in these studies. Many of the samples were irradiated at 6 or 8 Mev to investigate the various photoexcited metastable isomer products that are formed in appreciable yields by some elements. Other samples were irradiated at 12, 15, and 20 Mev, where (γ,n) products are predominant with most elements although (γ,p) products are also observed in some cases.

All the abundant elements found in geologic samples can be activated by gamma irradiation (Table 2). Sodium and manganese, which form very prominent activities in the thermal-neutron activation of

Table 2 Photonuclear Activation Reactions of Geologic Samples with 25-Mev Photons

Element bombarded	Reaction	Half-life of product isotope
Oxygen	$^{16}O(\gamma,n)^{15}O$	2.07 min
Silicon	$^{29}Si(\gamma,p)^{28}Al$	2.27 min
	$^{30}Si(\gamma,p)^{30}Al$	6.56 min
Aluminum	$^{27}Al(\gamma,n)^{26}Al$	6.7 min
Iron	$^{54}Fe(\gamma,n)^{53}Fe$	8.9 min
Calcium	$^{40}Ca(\gamma,n)^{39}Ca$	1.00 sec
Magnesium	$^{24}Mg(\gamma,n)^{23}Mg$	11.9 sec
	$^{26}Mg(\gamma,p)^{25}Na$	60 sec
Potassium	$^{39}K(\gamma,n)^{38}K$	7.7 min
Phosphorus	$^{31}P(\gamma,n)^{30}P$	2.55 min

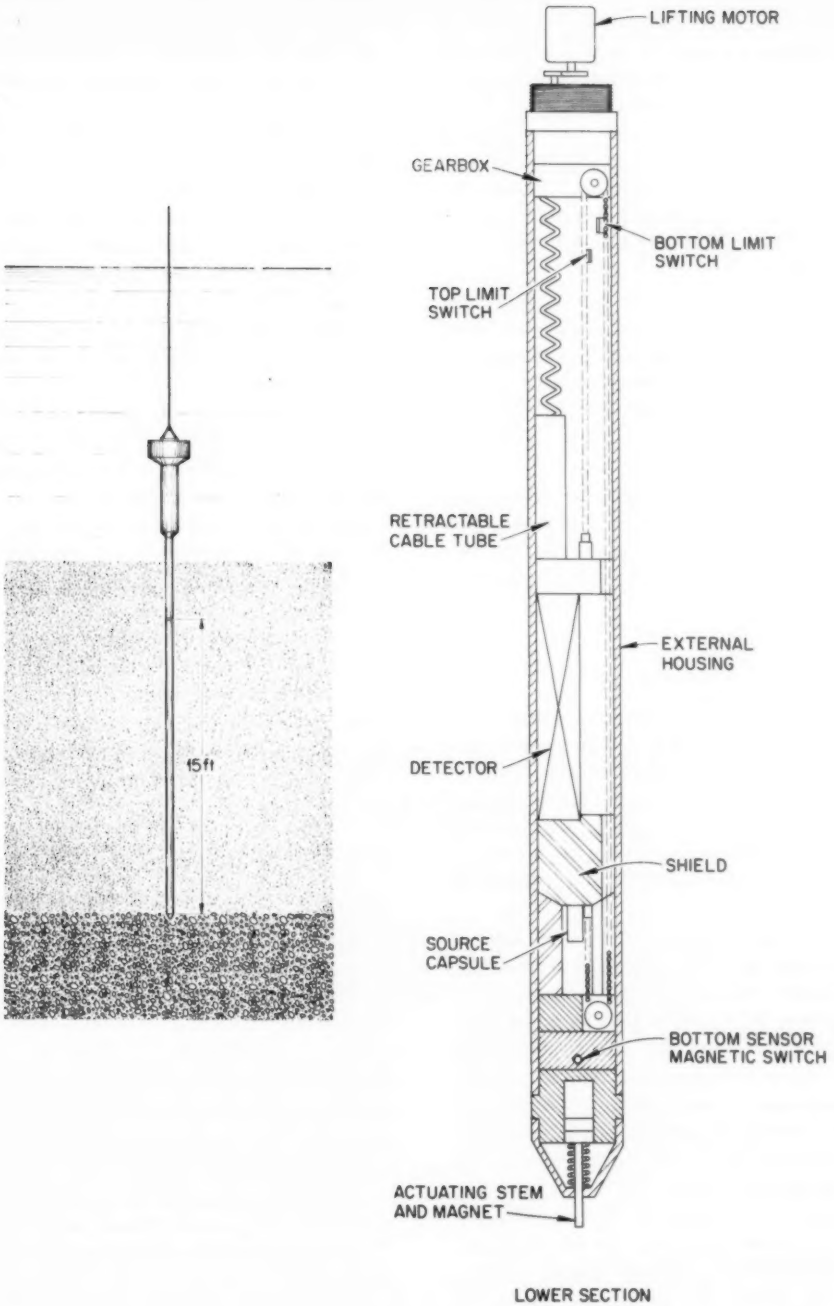

Fig. 15 Ocean-bottom sediment-density meter [described in *Isotopes and Radiation Technology*, 3(3): 216 (Spring 1966)].

geologic samples, form very little photon-induced activity. Most of the activities induced by photons in the major and minor elements of rocks produce rather short-half-life activities. This allows one to determine a number of trace elements instrumentally. Those which have longer-lived induced activities are determined with greater sensitivity. The problems of thermal-neutron self-shielding are eliminated in photonuclear work. The method can be made very selective since the threshold for gamma activation is quite distinct and varies from element to element.

Application of this technique to boreholes requires development of a linear accelerator to produce high-energy gamma rays. Although, at first thought, a borehole device of this kind seems exceedingly formidable, it is not completely out of the question, especially if one considers using a linear accelerator. Laboratory-analysis results reported in the Soviet literature are sufficiently encouraging to suggest that work on a prototype borehole tool is probably well under way in that country. It will be interesting to see if this can be engineered into a practical logging tool for commercial operations.

Ocean-Bottom Sediment Gage

A density gage using the backscattered gamma-ray technique has been developed to measure ocean-bottom sediments.[18] The device is similar to the gamma–gamma logging tool used for measuring cement surrounding a pipe casing. The mass physical properties of submarine sediments are of interest in understanding sedimentation and the geological history of ocean basins.

The density probe, which weighs 700 lb, has the appearance of a large dart. The upper part is a 5-ft-long 6-in.-diameter barrel, which houses the batteries. The lower part, which is 20 ft long and 3.5 in. in diameter, tapers to a cone, which enters the sediment first as the instrument is lowered. The radioactive source and gamma-ray detector are in the bottom 15 ft of the tube (Fig. 15). The intensity of the backscattered gamma radiation is proportional to the density of the sediment. The radioactive source is ^{137}Cs, and the detector consists of a bundle of 30 Geiger-Mueller tubes. When the probe penetrates the sea floor, the nose of the instrument is forced upward a short distance into the barrel, and a magnetic contact is made which starts the measuring cycle. The traveling detector and source are raised inside the barrel a total distance of 12 ft by a pitch roller chain stopping every 2 ft to make a 10-sec count. At each stop the backscattered gamma rays are detected by the G-M tubes, counted by a series of cascaded binary scales, and recorded by a camera on 8-mm film. A watch and an inclinometer are mounted in the data chamber, and the inclination of the probe and the time of each measurement are recorded by the camera. Upon reaching the top of its travel, the assembly reverses its direction and returns to the bottom of the probe. The entire cycle takes approximately 8 min. At the end of each cycle, the source comes to rest in a stationary shield, which reduces the radiation hazard during normal handling of the instrument. The cycle is not repeated again until the probe is raised and lowered and the bottom-sensing switch on the nose of the barrel is pulsed.

The instrument will operate for 8 hr and test 60 sites before it must be brought to the surface for recharging the batteries and removing the camera film. In the older method of taking core samples, the sampling rate was four to five per day, and the cores had to be transported to a laboratory for density measurement. The new method is rapid and relatively inexpensive and produces a continuous record that indicates minor trends as well as major variations in the density of the bottom sediments. The new gage was field tested at sites where density data had already been obtained by the older method. Density profiles of the layers of sediment penetrated by the probe agreed satisfactorily with values measured in the laboratory.

References

References marked with an asterisk were cited by the author but were not available to the Isotopes Information Center for bibliographic verification.

1. R. L. Caldwell and R. F. Sippel, New Developments in Radioactive Well Logging Research, *Bull. Amer. Assoc. Petrol. Geologist*, 42(1): 159-172 (1958).
2. R. L. Caldwell, Well Logging in USSR, Society of Professional Well Log Analysts—Transactions of the Eighth Annual Logging Symposium, June 11–14, 1967, p. C1-30 [*Eng. Index.*, p. 172 (June 1968)].
3. J. A. S. Adams and W. M. Lowder (Eds.), *The Natural Radiation Environment*, First International Symposium, Rice University, Houston, 1963, The University of Chicago Press, Chicago, 1964. (1069 pp.)
4. V. V. Larionov and M. D. Shvartsman, Natural Radioactivity of Carbonate Rocks, in *Radioisotope Instruments in Industry and Geophysics*, Symposium Proceedings, Warsaw, 1965, Vol. 2, pp. 305-322, International Atomic Energy Agency, Vienna, 1966 (STI/PUB/112).
5. V. V. Larionov, *Nuclear Geology and Geophysics* (Yadernaya geologiya i geofizika), V. N. Dakhnova (Ed.), Gostoptekhizdat, Moscow, 1963, 351 pp. [Monthly Index of Russian Accessions, 16: 3626*a* (1963–1964)].

6. V. A. Artsybashev, *Gamma-Method of Measuring Density* (Gamma-Metod Izmereniya Plotnosti), Moscow, Atomizdat, 1965, 201 pp. (*Chem. Abstr.*, 66: 69200*v*).
7. J. S. Wahl, J. Tittman, C. W. Johnstone, and R. P. Alger, The Dual Spacing Formation Density Log, *J. Petrol. Technol.*, 16: 1411-1416 (1964).
8. J. A. Czubek, Physical Possibilities of Gamma-Gamma Logging, in *Radioisotope Instruments in Industry and Geophysics*, Symposium Proceedings, Warsaw, 1965, Vol. 2, pp. 249-275, International Atomic Energy Agency, Vienna, 1966 (STI/PUB/112).
9. L. S. Allen, C. W. Tittle, W. R. Mills, and R. L. Caldwell, Dual-Spaced Neutron Logging for Porosity, *Geophysics*, 32: 60-68 (1967).
10. J. Tittman, H. Sherman, W. A. Nagel, and R. P. Alger, The Sidewall Epithermal Neutron Porosity Log, *J. Petrol. Technol.*, 18: 1351-1362 (1966).
11. P. Threadgold, Well Logging in Middle Eastern and Similar Large Reservoirs, Society of Professional Well Log Analysts—Transactions of the Eighth Annual Logging Symposium, June 11–14, 1967, p. F1-20 [*Eng. Index*, p. 172 (June 1968)].
12. *a*. P. A. Wichmann, E. C. Hopkinson, and A. H. Youmans, Advances in Nuclear Production Logging, Society of Professional Well Log Analysts—Transactions of the Eighth Annual Logging Symposium, June 11–14, 1967, p. T1-10 [*Eng. Index*, p. 171 (June 1968)].
b.*J. S. Wahl, A. H. Fentrop, C. W. Johnstone, and R. J. Schwartz, The Thermal Neutron Decay Time Log, Paper 2252 presented at the 43rd Annual Fall Meeting of the Society of Petroleum Engineers, Houston, Tex., Sept. 29–Oct. 2, 1968.
13.*W. F. Baldwin, R. L. Caldwell, E. E. Glenn, J. B. Hickman, and L. J. Norton, Slim Hole Logging in Colorado Oil Shale, Society of Professional Well Log Analysts—Transactions of the Seventh Annual Logging Symposium, May 1966, p. C1-17.
14. M. P. Tixier and R. P. Alger, Log Evaluation of Nonmetallic Mineral Deposits, Society of Professional Well Log Analysts—Transactions of the Eighth Annual Logging Symposium, June 11–14, 1967, p. R1-22 [*Eng. Index*, p. 161 (June 1968)].
15. R. L. Caldwell, W. R. Mills, Jr., L. S. Allen, P. R. Bell, and R. L. Heath, Combination Neutron Experiment for Remote Analysis, *Science*, 152: 457-465 (1966).
16. J. I. Trombka and R. L. Schmadebeck, A Method for the Analysis of Pulse-Height Spectra Containing Gain Shift and Zero-Drift Compensation, *Trans. Amer. Nucl. Soc.*, 10: 33-35 (1967).
17. V. P. Guinn and G. H. Anderson, Photonuclear Activation Analysis of Geologic Samples Using the LINAC, *Trans. Amer. Nucl. Soc.*, 10: 23-24 (1967)
18. B. F. Wilson, A Sediment Density Meter, USAEC Report ORO-622, Lane-Wells Company, April 1964.

Use of Radioisotopes in the Measurement of Wool Growth*

By A. M. Downes, W. H. Clarke, and T. C. Daggt

Abstract: *A method for measuring the rate of growth in length of individual wool fibers is described. Radioisotope-labeled amino acids are injected into the animal, and autoradiograms are made of the fibers at various intervals of time.*

Until recently, most studies of the rate of wool growth relied on the technique of repeatedly clipping the wool grown over a period of several weeks on a defined area of skin. However, this technique is not sufficiently accurate for the measurement of wool grown over periods of a few days and has the further disadvantage that the clipping may cause a change in the rate of wool growth, especially under cold conditions.

The rate of growth in length of individual fibers can now be measured accurately by periodic injection of experimental animals with radioisotope-labeled amino acids, followed by autoradiography of the fibers. This method was first described by Rougeot[1] and by Downes and Lyne[2,3] for wool growth, but it has since been applied also in studies on hair growth in various mammals, including man.[4-7]

Method

The method is based on observations made about 10 years ago by Bern, Harkness, and Blair[8] and by Ryder,[9] who injected cystine-^{35}S into mice and found that some of the ^{35}S was incorporated rapidly into the hair follicles, just below the point where the hardening or keratinization of the growing hair is completed.

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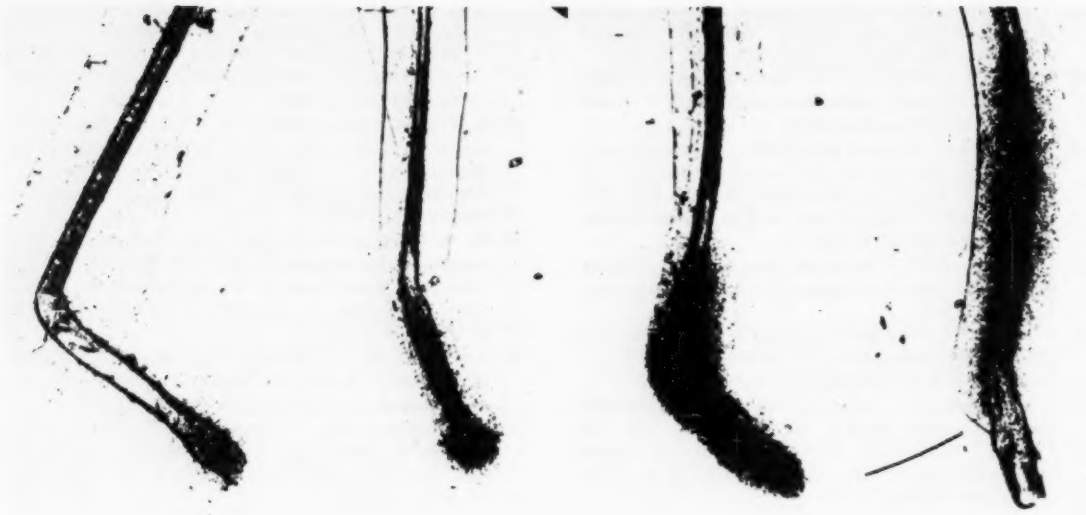


Fig. 1 Autoradiograms of wool fibers plucked at various time intervals after intravenous administration of L-cystine-^{35}S (350 μc) to a sheep. Unstained. Plucking times were, left to right: 3 min, 1 hr, 4 hr, 30.5 hr.

When cystine-^{35}S is injected into the bloodstream of a sheep, within a few minutes some radioactivity can be detected in and just above the base of the wool roots. This can be demonstrated by autoradiography of skin sections or of plucked fibers (Fig. 1). In later samples, radioactivity is present further and further up the follicle until, after about an hour, some ^{35}S is present throughout the unkeratinized part of the wool root. From then on, while radioactivity continues to be incorporated into the follicle from the bloodstream, the front of the radioactive zone moves out of the skin with the fiber.[10] There is no further incorporation of cystine into the cells beyond the keratinization zone. Autoradiograms of fibers plucked several days after the injection show a zone of relatively intense labeling, trailing away to progressively less radioactive regions. A second dose, given a few days later, produces another intensely labeled zone, whose front can be identified easily in spite of the presence of some radioactivity from the preceding dose (Fig. 2).

The distances between the points on the autoradiograms corresponding to successive doses can be measured accurately on a projection microscope. The beta particles from the radioactive decay penetrate some distance into the emulsion of the film, producing a fuzzy image. Different observers may choose slightly different points as representing the injection time, but this is done with consistency; the mean results agree well. The diameter may also be measured, on a projection microscope, at positions on the fiber corresponding to precisely known times.

Advantages of Method

The autoradiographic method has several advantages:

1. Accurate measurements can be made of any changes in the rate of growth of individual fibers over periods as short as 2 to 3 days.

2. The growth rate of adjacent fibers in the same body region or of fibers from different regions can be compared because each dose, in effect, puts a simultaneous timing mark, accurate to within ±2 hr, on the fibers that are growing on the animal at the time of the injection. In sheep the wool- and hair-growing regions can be compared.

3. The samples do not have to be taken until some time after the last dose has been given, thereby avoiding disturbance to the sampled sites while the experimental treatments are being imposed.

4. The fiber is preserved, so that successive short lengths can be measured on the same fiber. Since the fiber diameter can also be measured at precisely known points in time, the relations between changes in length, growth rate, and diameter can be accurately determined.

5. Fibers in relatively inaccessible positions can be studied. The best example of this is the administration of cystine-^{35}S to a pregnant animal, in which the fibers growing on the fetus as well as those on the mother are labeled. This valuable approach to the study of the development of follicle activity and of rate of wool growth in lambs before birth has been used by Paducheva[11,12] and by Side and Rudall.[6]

Doses

In most of the experiments in which this method has been applied, cystine-^{35}S has been used but methionine-^{35}S would also be suitable. These, as well as other amino acids labeled with ^{14}C or ^{3}H, are incorporated into hair or wool proteins. However, the beta particles emitted by ^{3}H are too weak to produce clear autoradiographic images on intact fibers. Other ^{14}C- or ^{35}S-labeled precursors that are rapidly converted to amino acids could also be used, but no systematic search for the most suitable of these compounds has yet been made.

Quite small doses of cystine-^{35}S—of the order of 10 μc—given to adult sheep intravenously have proved sufficient for making autoradiograms with exposures of several weeks. The amounts of radioactivity needed are so small that radiation effects are unlikely to be a problem. The great sensitivity of the method may be judged from the fact that a Merino sheep has about 50 million fibers,[13] most of which are growing and can show every dose on the autoradiogram. Since ^{35}S has a half-life of about 3 months (87.1 days), the dose has to be doubled for an experiment lasting 3 months, quadrupled for one lasting 6 months, and so on.

For longer experiments, cystine-^{14}C may be used. Since ^{14}C has a half-life of more than 5000 years, it places a "permanent" time mark on the fibers, and the autoradiogram can be made at any convenient future time. This has obvious advantages and is worthwhile in certain types of experiments even though cystine-^{14}C is about 10 times as expensive as cystine-^{35}S. One way of decreasing the amount of radioactivity needed is to restrict the effective labeling to small regions by injecting the dose subcutaneously[1] or intradermally.[14] Intradermal doses of 0.1 to 0.5 μc of cystine-^{14}C have proved to be satisfactory, although much smaller doses than this could be used. Because of the negligible radiation hazard, direct injection into the skin is suitable for studying hair growth in human subjects.[7] However, this method of injection should be used with care because the skin may be damaged sufficiently to alter the rate of hair (or wool) growth if too many

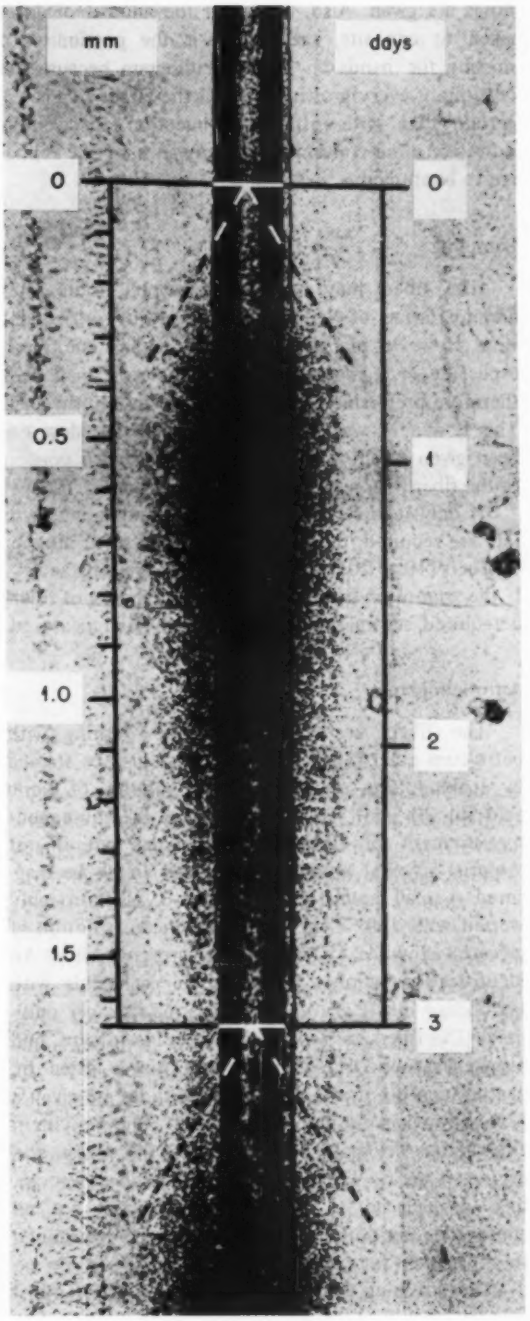


Fig. 2 Autoradiogram of a sheep vibrissa (whisker) showing the method of measuring the length grown in 3 days. The sheep had received two doses of cystine-^{35}S, 3 days apart. (After Downes and Lyne.[2])

doses are given. Also, the larger the number of doses given to one site, the greater is the possibility of missing the bands on the autoradiogram because the labeling of every growing fiber in the target area is less certain than with intravenous injection. Intravenous doses are more convenient if many sites on one animal are to be studied.

Sampling

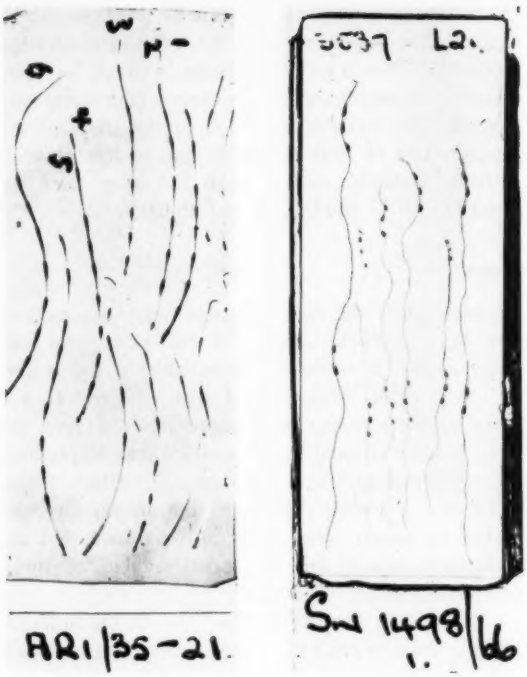
The fibers may be plucked several hours after administration of the last dose or at any subsequent time. However, plucking will usually break some fibers, especially in regions where the diameter is small. It is therefore preferable to clip the fibers close to the skin. This is done 2 weeks or more after the last dose has been given to allow the most recently labeled portion of the fiber to appear above the skin surface.

If only relative measurements of changes in growth rate are required, the mean results for a small number of fibers (10 to 20) selected at random are satisfactory. If the true mean growth rate for a population of fibers is required, several hundred of them must be measured.

Autoradiography

The fibers are first cleaned by washing with petroleum ether (Shell X2). They may also be stained by soaking in a saturated aqueous solution of picric acid for 30 min. The staining makes the subsequent measurement of fiber diameter easier but is not essential if only length growth rates are to be measured. A small bundle of fibers (10 to 20) is thoroughly wetted with 1 to 2 ml of a 10% aqueous solution of glycerol–albumen (50:50) on a microscope slide. An identification number is written on each slide with radioactive ink (e.g., 0.1 μc of cystine-^{14}C per milliliter). The fibers are separated, using fine forceps, and placed in rows. The albumen solution is dried by heating at 40°C for 2 days, and the slides are given a protective cover by dipping them in 0.5% pyroxylin in ether–ethanol (75:25), draining away the excess, and drying at 40°C. Then, in a photographic darkroom, they are placed in contact with a film for an appropriate exposure time, which has to be determined by experiment for each batch.

The stripping film technique (Kodak AR50 film) (Fig. 3*a*) may be used, but a simpler and more sensitive procedure, in which an X-ray film is placed in contact with a number of slides in a cassette, is usually preferred. We have obtained the most satisfactory results with Kodak Industrial X-ray Films, Type AA or



(a) (b)

Fig. 3 (*a*) Stripping-film autoradiogram of vibrissae from a sheep that has received nine intravenous doses of cystine-^{35}S at 4-day intervals. Since vibrissae take about a month to complete their growth, the number of doses registered on the autoradiogram depends on the degree of synchronization of the growth and labeling periods. (*b*) Autoradiogram with X-ray film of wool from a region of the skin of a sheep that had been dosed intradermally with cystine-(3-^{14}C). The film was mounted so that the autoradiographic images are contiguous with the fibers. Two groups of three doses (4-day intervals), separated by 6 weeks, were given. Note that two of the fibers do not show the six doses. This is due to the difficulty of labeling every growing fiber in the target area with intradermal doses.

Crystallex, because of their low fog level and fine grain size. The film is developed, fixed, washed, and dried (Fig. 4). The pieces of film corresponding to each slide are cut out and remounted on the slide with DPX mountant[15] so that the autoradiographic images coincide with the outlines of the fibers. Finally, a glass cover slip is mounted over the film with DPX to produce a permanent record (Fig. 3*b*).

The contact-autoradiography technique may also be applied to bundles of wool. A typical example is presented in Fig. 5, which shows such an autoradio-

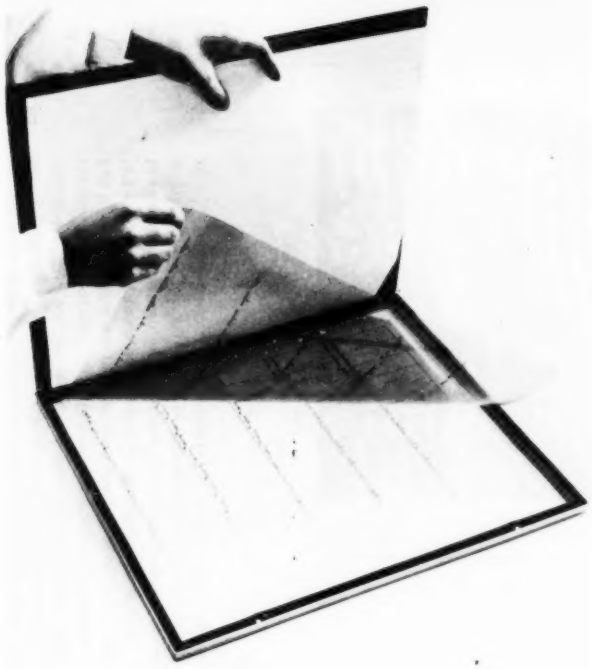


Fig. 4 A cassette full of prepared slides, with the corresponding processed film.

gram and the corresponding bundle of wool clipped from a sheep that had received 19 doses of cystine-^{35}S at various time intervals. Each dose produces a dark band on the film. Successive bands corresponding to doses given as little as 4 days apart can be seen readily if the rate of wool growth is fast enough. This method offers a more precise alternative to the widely used dye-banding procedure[16] for experimental studies of wool growth, especially in measuring the time required to form a complete crimp, or wave, in the wool.

Application

The above techniques are used routinely at the Ian Clunies Ross Laboratory, C.S.I.R.O., Division of Animal Physiology, at Prospect, N.S.W., in studies such as the effects of nutrition, hormones, and climate on wool growth. Much precise information on the growth of individual fibers is now being obtained.

The autoradiographic technique, with regular doses of cystine-^{14}C, can provide a complete history of the growth rate of each fiber over a period of years. So far, however, the studies have been chiefly concerned with normal variations in wool growth over short periods and the rate of response of wool growth to nutritional changes. In practice, times of 3 to 7 days between doses have proved to be most useful, although accurate results have been obtained with times as short as 1.5 days.

An example of the type of experimental results obtained using this technique is shown in Fig. 6. A sheep was given four intravenous doses of L-cystine-^{35}S at 7-day intervals during a period of low food intake. On the day of the fourth dose, the sheep's ration was increased substantially and kept at a constant level for the next 14 weeks, during which time more doses of cystine-^{35}S were given. After the experiment, some of the fibers on the mid-side of the sheep were taken and autoradiographed, and length growth rates and diameters were measured. The rate of growth in length rose about 10% in the first 4 days after the food intake was increased and within 2 weeks had become constant at 38% above the initial rate. An interesting feature of the results was that the percentage increase in the length growth rate was much larger for the smaller than for the larger fibers. There was also a rapid increase in fiber diameter after the food intake was increased.

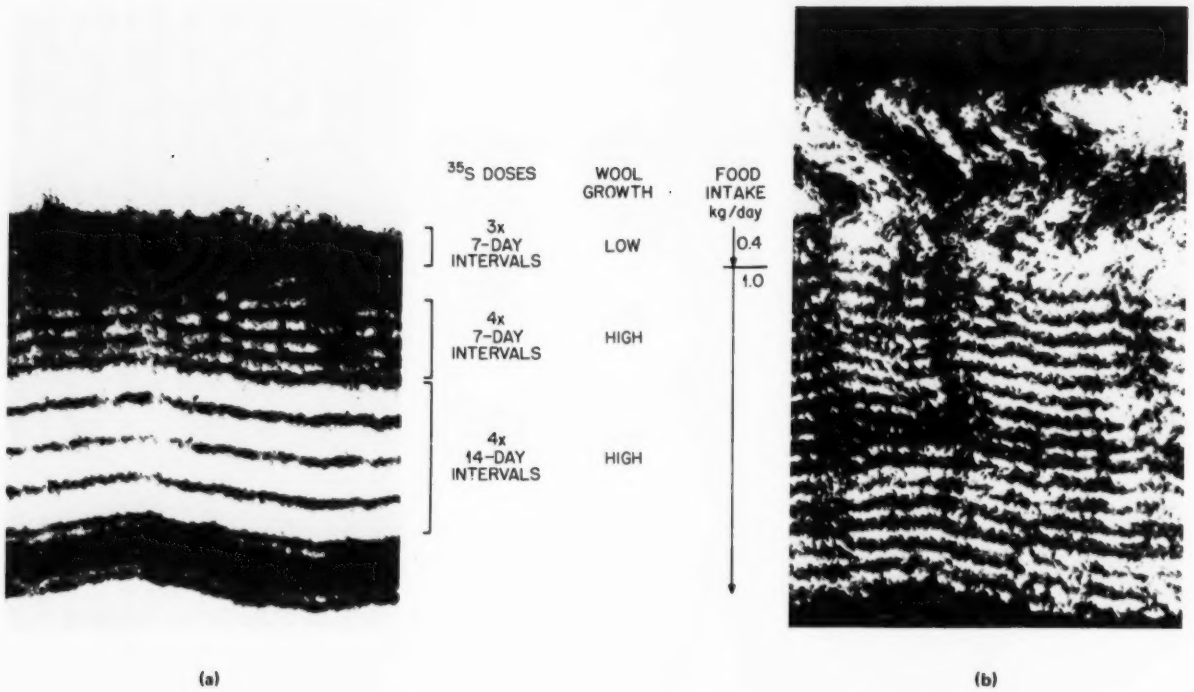
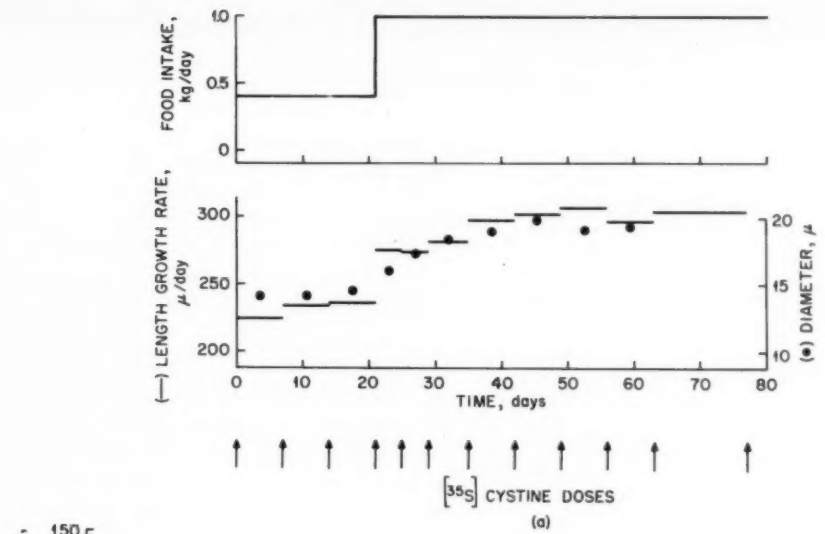


Fig. 5 (*a*) Autoradiogram of a bundle of wool clipped from a sheep that had received 19 intravenous doses of cystine-^{35}S at various time intervals. The first four doses were given at 7-day intervals during a period of restricted food intake, when the rate of wool growth was low. On the day of the fourth dose, the food intake was raised from 0.4 kg/day to 1.0 kg/day and then kept at the higher level to produce a substantial increase in the wool growth. More doses of cystine-^{35}S were then given at intervals of 4, 4, and 6 days, followed by four 7-day and four 14-day intervals. Finally, another four doses were given at intervals of 5, 4, 4, and 6 days. Each dose produced a dark band on the autoradiogram. The individual bands corresponding to the first four doses cannot be seen clearly, but those corresponding to the later doses, when wool growth was much faster, are well separated. (*b*) Corresponding bundle of wool, which is longer than shown in the autoradiogram because several months' wool growth was already present on the sheep at the time of the first injection. The time required for the formation of each crimp, or wave, on the wool can be measured accurately by reference to the autoradiogram. Other aspects of this experiment are illustrated in Fig. 6.



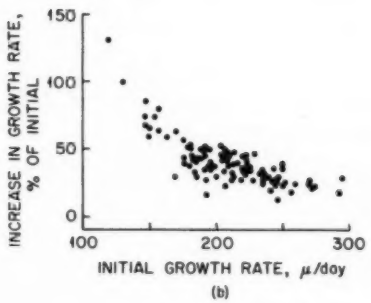


Fig. 6 Effect of increase in food intake on rate of wool growth. (*a*) Mean length growth rates and diameters of 50 wool fibers from a sheep during 77 days. Food intake was increased on day 21, and intravenous doses of cystine-^{35}S were given at the times indicated by the arrows. The average length growth rate increased from 230 μ/day to 300 μ/day and the average diameter from 14 μ to 19 μ. (*b*) Individual increases in length growth rate for 100 fibers from above experiment, showing differential response.

References

References marked with an asterisk are not available in the Isotopes Information Center.

1. *J. Rougeot, *Ann. Zootech.*, 8: 175 (1959).
2. A. M. Downes and A. G. Lyne, Measurement of the Rate of Growth of Wool Using Cystine Labelled with ^{35}S, *Nature*, 184: 1884-1885 (1959).
3. A. M. Downes and A. G. Lyne, Studies on the Rate of Wool Growth Using ^{35}S-Cystine, *Aust. J. Biol. Sci.*, 14: 120-130 (1961).
4. *E. Johnson, in *Biology of the Skin and Hair Growth*, p. 491, A. G. Lyne and B. E. Short (Eds.), Angus and Robertson, Sydney, 1965.
5. *G. C. Priestley and K. M. Rudall, *ibid.*, p. 165.
6. H. J. A. Side and K. M. Rudall, Rates of Hair Growth, in *Progress in the Biological Sciences in Relation to Dermatology—2*, pp. 337-354, A. Rook and R. H. Champion (Eds.), Cambridge University Press, London, 1964.
7. D. D. Munro, Hair Growth Measurement Using Intradermal ^{35}S-Cystine, *Arch. Dermatol.*, 93: 119-122 (1966).
8. H. A. Bern, D. R. Harkness, and S. M. Blair, Radioautographic Studies of Keratin Formation, *Proc. Nat. Acad. Sci. U.S.*, 41: 55-60 (1955).
9. M. L. Ryder, Use of Radioisotopes in the Study of Wool Growth and Fibre Composition, *Nature*, 178: 1409-1410 (1956).
10. A. M. Downes, A. G. Lyne, and W. H. Clarke, Radioautographic Studies of the Incorporation of ^{35}S-Cystine into Wool, *Aust. J. Biol. Sci.*, 15: 713-719 (1962).
11. A. L. Paducheva, Use of Labeled Sulfur To Study Growth of Wool of Lambs in Utero and After Birth (in Russian), *Dokl. Akad. Nauk SSSR*, 137: 484-487 (1961).
12. *A. L. Paducheva, *Ovchevodstvo*, 8(10): 25 (1962).
13. H. Weiler, R. E. Chapman, and J. M. Doney, The Total Number of Fibres on Sheep, *Aust. J. Agr. Res.*, 11: 628-635 (1960).
14. A. M. Downes, L. F. Sharry, and A. R. Till, The Fate of Intradermal Doses of Labeled Amino Acids in Sheep, *Aust. J. Biol. Sci.*, 17: 945-959 (1964).
15. C. F. A. Culling, *Handbook of Histopathological Techniques*, 2d ed., p. 171, Butterworths, London, 1963.
16. R. E. Chapman and J. L. Wheeler, Dye-banding: A Technique for Fleece Growth Studies, *Aust. J. Sci.*, 26: 53-54 (1963).

Use of Tracer Technique in Soil Erosion Research*

By J. Roger McHenry†

Abstract: *Techniques used to study erosion by tagging soil with radioactive tracers are reviewed. Several nuclides have been used for this purpose, e.g., ^{59}Fe, ^{46}Sc, ^{198}Au, and ^{51}Cr. Guidelines to be followed in the selection of a tracer are reviewed, and methods of incorporating the isotope on the material to be traced are described. Studies are discussed in which both the movement of single grains of sand and the bulk movement of the soil are followed.*

While movements of sands and sediments on beaches and in flowing streams have been traced with radioisotopes in many studies,[1] this method has been used in only a few studies of soil erosion. This paper reviews these studies.

The principles involved in the selection of a good tracer are first discussed, and this is followed by a description of methods for attaching the tracer to the soil. The methods used for studying soil erosion with tracers are then reviewed, and the paper concludes with an evaluation of the methods.

Principles of Tracer Selection

One of the most important factors in using a tracer technique is the choice of the proper tracer. The ultimate goal, of course, is to have the tracer act in every respect like the population being traced. However, no tracer is, in all respects, exactly like the population being traced. For example, tritium (^3H) is used extensively as a tracer for water. Tritiated water (HTO), except for the replacement of ^1H atoms by ^3H atoms, is indistinguishable from normal water by any gross test or comparison. However, it has been found that HTO does not act precisely as H_2O. The properties of ^3H are sufficiently different from those of ^1H that some segregation of HOH and HTO occurs. Tritium is often said to be the ideal tracer for water as it is incorporated in water itself; fortunately for practical purposes this statement is true. As a result, tritium has been used successfully in many studies of underground, surface, and vapor movement of water.

Characteristics of a Good Tracer

A good tracer must have a half-life sufficiently long so that the desired experiment can be completed without undue loss of accuracy through reduced activity of the tracer, but the residual radioactivity should be minimal after the experiment is completed. To achieve this, a minimum quantity of radioactivity may be used, the activity may be recovered and disposed of, or the radioisotope used may decay in a short time. The last choice is preferred since the first method may preclude achieving adequate counting rates, and the second alternative may be expensive or difficult to perform.[2]

The specific activity, or rate of disintegration per unit weight or volume, is also important in selecting an isotope. Generally speaking, the greater the specific activity of the radioactive tracer used, the better its performance. In any tracer study the ratio of tracer added to total material being traced should be as low as the detection technique will allow. The number of tracer units should not be so plentiful as to alter in any way the behavior of the material under test.

The types and energies of emissions associated with the tracer are usually selected on the basis of ease of detection. This implies, of course, that freedom of choice of a tracer exists. Often, however, very restrictive circumstances are encountered, and then the use of a particular radioisotope dictates the counting equipment needed.

In general, alpha emitters are avoided as tracers because they are more difficult to measure and they are a greater radiological hazard.

Beta emitters are numerous and can be detected with a high degree of efficiency. Because of the generally lower energies of their radiations, larger amounts of beta emitters (e.g., higher specific activities) than of gamma emitters can be used. Beta emitters are usually easily shielded. Identification of each of several beta emitters in a sample is possible by using their energy differences. Thus ^{14}C and ^3H may be determined in the same sample because the

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maximum energies of ^{14}C and ^{3}H differ by an order of magnitude. For laboratory experiments, when detection sensitivities are less critical than in the field, the use of beta emitters is most effective.

Gamma emitters are recommended where a penetrating, energetic radiation is needed. Gamma rays can be detected with great sensitivity by scintillation techniques. Thus only very small amounts of gamma activity are needed per unit weight (or volume) of the system and are more easily measured in situ. Because of their penetrating ability, however, the emitted gamma rays do require more shielding.

The chemical and physical forms of the tracer used are an extremely important consideration, and the incorporation of a particular radioisotope into a system under study may involve processing the radioisotope to put it in the desired form.

In addition to the above considerations, the radioisotopes selected for tagging sand particles, for example, should:

1. Be in an insoluble compound.
2. Have a high relative MPC (maximum permissible concentration)—that is, be relatively biologically harmless.
3. Be readily available. Not all radioisotopes can be readily purchased through commercial channels.
4. Have a low unit cost.
5. Not be readily exchanged with or adsorbed by other components in the system under test.

Calculation of the Amount of Tracer Required

The calculations involved in a radioactive tracer study must involve a careful consideration of all aspects of the experiment. The choice of isotope, its form, and the type of counting equipment available influence the calculations. The experimental worker is concerned with maximum accuracy, maximum sensitivity, and minimum radiological exposure. Good statistical reliability is sought with a minimum of counting time.[2]

A primary consideration in a tracer experiment is the maximum allowable error. This is related to the random decay rate of the radioisotope and the signal-to-noise ratio of the detector. In effect, this controls the minimum count rate compatible with the desired result. For most studies, the amount of time available for a measurement is limited. The necessary minimum number of observed events then controls the count rate needed.

For example, assume that the standard deviation, σ, of the observed signal can be as large as ±20% of the total count. For this test, also assume a limit of 5 min counting time per sample and a background of 50 counts/min. We may relate these as:

$$\sigma = \sqrt{\frac{\text{gross counts/min (sample + background)}}{\text{sample counting time, min}} + \frac{\text{background, counts/min}}{\text{background counting time, min}}}$$

If X = counts/min required, then

$$0.20X = \sqrt{\frac{50 + X}{5} + \frac{50}{5}}$$

and

X = 25 counts/min or the count required over background count

If a limit of ±1% is assumed for the value of σ, a net count of 2095 counts/min will be needed. If the time of counting is limited to 1 min, 10,200 net counts/min will be required. If background is ignored, the net count required is 10,000 counts/min for σ = 1% for a 1-min count.

To ensure that the calculated count rate is obtained, sufficient radioactivity must be added to the system so that a sample of the system will contain more than the minimum required radioactivity. If a measure of the radiation intensity of the material is taken in situ, the geometry of the detector system must be sufficient to yield the minimum value.

For example, the top inch of the surface of a 0.01-acre plot would have to receive an application of tracer in excess of 3.2×10^8 counts/min so that a random 10-g sample would yield the necessary 2095 counts/min with a σ of 1% for a 5-min count. Many counters are only 1 to 10% efficient; so this activity would likely be increased to 3×10^{10} counts/min. For most radioisotopes this would require 10 to 50 mc of activity.

The practical problem here, of course, is how one applies 10 mc of radioactivity uniformly over a 0.01-acre plot. Obviously the radioisotope must be in solution, otherwise anything approaching uniform distribution would be impossible.

Tracers in Erosion Research

Erosion research is concerned primarily with a study of the detachment and initial movement of soil

particles; their transport is usually of lesser significance. Deposition of particles, except for that during the early stages of transit, is also of lesser significance. Primarily, then, interest is in following the movement of particles from a position on, or in, a field to a position essentially off, or out of, the field in question. Usually the concern is with a small watershed or experimental plot.

Tagging techniques most often reported in the literature[3] are largely confined to primary particles (usually sand) because they are more readily tagged. These larger particles may, or may not, be aggregated into secondary particles.

Selection of Radioisotope

The properties of a good tracer have been enumerated. A number of radioisotopes have been used for tracing the movement of soil, sediment, or water. The pertinent properties of these radioisotopes are given in the literature.[4]

Radioisotopes which have one or two beta or gamma emissions are preferred for use in tracer studies. For most erosion research work, the greater the energy of emission, the easier the detection of the radioactivity.

Preparation of Tagged Particles

The following methods are available for tagging sand, clays, or silts so that their movements can be traced:

1. Irradiation, with neutrons, of sand grains or of simulated sand grains made from glass.
2. Fixation of a radioisotope on the surface of particles.
3. Adsorption of radionuclides on clays or silts.

Each of these techniques has special advantages and has been used in preparing tracers.

Neutron Activation. It is possible to use the natural radioactivity of some materials as a tracer. However, natural levels of radioactivity are usually quite low. One can induce in a selected material radioactivity of various levels by exposing it to neutron bombardment for various times and at various flux levels. The user of a tracer radioisotope usually has specific goals for the irradiation in terms of the isotope, specific activity, and total activity required. Knowing the conditions of irradiation, it is possible to estimate the amount of target material needed and the time of irradiation. For practical purposes an irradiation time of about six product half-lives results in maximum product production.

The activated sand particles have the same hydraulic characteristics as the sand being traced because the sand is usually taken from the area of study. The choice of radioisotopes is limited, but the specific activity can be varied considerably. The cost and time of irradiation can be appreciable, and rather large and expensive containers are needed to safely handle large amounts of irradiated sand.

Particles can be tagged by exposing them to neutrons from a nuclear reactor, a neutron generator, or an isotopic neutron source for the calculated period. Sand and silt seldom contain sufficient numbers of atoms suitable for activation. It is more efficient to use a synthetic sand, i.e., glass which contains the atoms desired for tracing. The glass containing the desired atomic species, say, scandium, is crushed and sieved, and the particles of desired size are irradiated to produce ^{46}Sc-labeled particles.[5,6] Almost any element which will form a melt with a silicate can be used.

Large volumes of material can be irradiated and used to follow movements of erosion particles in mass. The activity per particle is generally not great, but the total activity involved is frequently in the curie range. For example, for a 100-μ-diameter glass sphere containing 5% Sc_2O_3, irradiation for 10 days at a flux of 2×10^{13} n/(cm^2)(sec) will produce an activity of 3.2×10^{-4} mc/particle or 0.23 curie/g. This is much less activity per particle than that obtained by surface bonding (to be described),[7] perhaps as much as two orders of magnitude.

Surface Bonding. Some types of radioactivity can be bonded to the surfaces of sand- and silt-sized particles by chemical or physical means. Rather high specific activities (much greater than for irradiated sand particles) can be achieved so that individual particles are readily identifiable. Preparation of such particles is not difficult, but the permanency of "fixation" of radioactivity is less than by direct irradiation of the scandium-glass spheres. Preparation of small numbers of "tagged" particles is feasible—something not economical with irradiation methods. The hydrodynamic characteristics of the tagged particles are unchanged by the surface tagging procedure, and a wide variety of isotopes can be used.

Scandium-46 has been used in the USDA Sedimentation Laboratory[7,8] to tag sand particles. In the bonding treatment,[7] the sand is mixed with a solution of $^{46}ScCl_3$, evaporated to dryness, and ignited at 1050°C. This technique is readily performed in a

chemical laboratory. Only relatively small amounts of material can be tagged at any one time, but the specific activity per particle achieved can be considerably greater than that obtained by irradiation of natural or synthetic materials.

Gilbert and coworkers[9] tagged sand with ^{110m}Ag. The sand was mixed with $^{110m}AgNO_3$ and a suitable reducing agent; a metallic silver coating was deposited on the sand when the mixture was exposed to sunlight. From 50 to 70% of the isotope adhered to the sand. Using similar techniques, Bougault et al.[10] have coated both sands and silts with ^{51}Cr and ^{198}Au, Götte and Becker[11] have coated sands with ^{46}Sc, ^{95}Zr, and ^{140}Ba, and Campbell[12] has tagged sands with ^{140}Ba, ^{64}Cu, ^{198}Au, and ^{51}Cr.

Adsorption Labeling. If the particles are small, e.g., clay or fine silt, the adsorption or exchange capacity of the system can be used to fix the activity. Krone[13] describes a method of tagging silt and clay with ^{198}Au. Wooldridge[14] used the adsorption of ^{59}Fe by the clay to study overland movement of soil particles.

Small clay spheres, on which the desired radioisotope has been adsorbed, can be converted to inert ceramic bodies by firing at a high temperature.[15] The size of the spheres can be controlled closely, but the hydrodynamic characteristics of these spheres are different from those of the naturally occurring soil particles.

Distribution of Tagged Particles

Where large amounts of activity are used to trace particle movement, considerable thought must be given to the method of distribution of the tracer in the area under test.[13,16] Usually the tagged particles are diluted with inert particles, and the mixture is then added to the experimental area. However, solutions containing the radioactivity can be added directly[14] if adsorption by clay or silt is to be the tagging method.

It is customary to monitor the area to be "seeded" with radioactive particles before and after the treatment. Subsequent measurements are made to determine the dispersal or movement of the added radioactivity.

Identification

Two methods of radioactive detection[17,18] are possible—measurements made in situ and measurements made on samples. Measurements in situ have the advantage of providing immediate results. Although laboratory measurements of radioactivity are more precise, sampling may introduce errors of considerable magnitude.

At the USDA Sedimentation Laboratory, we have made both types of measurements. For in situ measurements of radiation, our research has been the development of portable instruments of increasingly greater sensitivity. In the laboratory, our procedures have become more sophisticated, automated, and precise.

For field erosion studies, the use of gamma emitters is recommended. Because of their great penetrating ability, gamma emitters are more readily detected at greater distances and through thicker overburden. Furthermore, differential gamma spectrometry[19] provides the research worker a powerful tool for identifying simultaneously the concentrations of more than one gamma emitter. Using a differential gamma spectrometer (Fig. 1), we have readily distinguished and measured particles tagged with ^{46}Sc and

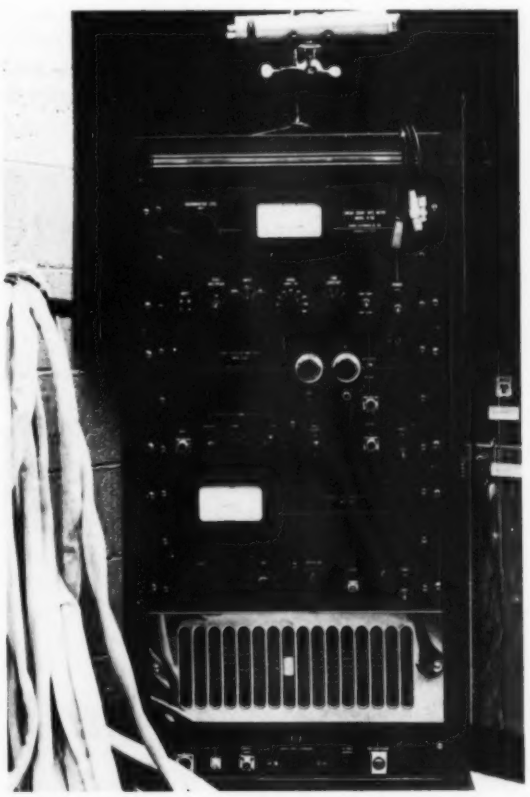

Fig. 1 Gamma differential scintillation spectrometer and detection probe.

^{110m}Ag. By this method (Fig. 2), we can distinguish the simultaneous movement of two sizes of particles or the contributions to erosion production from two sources.

Data Reduction

Determination of the presence of a tracer and its concentration generally does not provide the desired answer to the problem. Rather, the research worker must relate these findings to the experimental system. Movement of the fastest tagged particle is not a measure of the quantity of material moved. Some criterions are necessary. If one relates accumulated activity to time, a significant change may be postulated when 1, 10, or 50% of the expected activity is observed. For example, consider the removal of soil from a runoff plot whose surface has been tagged to a depth of 1 in. with a radioisotope. The first appearance of radioactivity in runoff waters is not a quantitative measure of soil removal: one must consider the accumulation of activity. If 0.01 of the added activity is collected in the runoff waters, one might assume something like 1% of the tagged soil volume has been removed from the plot. This volume of soil must be related then to the runoff plot in order to calculate a probable erosion susceptibility.

Applications

Radioisotopes have been used as tracers in a large number of commercial, industrial, and research situations.[2,20] The potentials of radioisotope technology in water resources have been reviewed.[21] Most of the work covered applies to the determination of sediment transport in streams or harbors.[1] Hubbell and Sayre[22] describe the use of the radioisotope ^{192}Ir to follow sand movement in a stream. Curry[23] used ^{46}Sc for tracing movement of clay through porous mediums. In 1961 a symposium was sponsored by UNESCO on the use of modern techniques for determining sand and silt movement along the coast, in estuaries, and in rivers.[24] Putman and Smith[5] and Lean and Crickmore[6] describe the use of radioactive tagged sand for hydraulic studies. These are typical, but not inclusive, uses of radioisotopes as tracers in erosion research.

In the USDA Sedimentation Laboratory, we have followed the movement of individual sand particles tagged with ^{46}Sc in experimental watersheds.[7] In preliminary tests, 10 sand particles were placed in a

Fig. 2 Using scintillation probe to monitor soil erosion plot for ^{46}Sc- and ^{110m}Ag-tagged particles.

small field rill at a depth of about 1 in. After 3 weeks, 5 of the 10 particles were recovered, and 1 of these 5 particles had moved about 50 ft. The other 5 particles were either buried too deep or had been removed from the field. These early measurements were made with particles having an activity of 2000 to 3000 counts/(min)(particle). Currently, activities of 100 to 200 thousand counts/(min)(particle) are being made. These particles can be detected through 35 to 40 cm of water or 6 to 8 cm of soil.

Frere and Roberts[26] used ^{90}Sr from fallout to study the movement of soil from an experimental watershed.

Wooldridge[14] studied erosion on a test site by pouring a solution of $^{59}FeCl_3$ in 0.1*M* HCl on the soil and then following the movement of the ^{59}Fe. He found that the activity was firmly attached to the silt and clay fractions of the soil, and he followed the movement of the soil for about 8 weeks.

DePloey[27] used artificial sand (glass) containing ^{46}Sc to study erosion by rain in the Western Congo. Using this tracer and detecting the particles by autoradiography, he showed that the erosion was caused by splash erosion and by dispersed and intermittent runoff.

In most cases, qualitative information relative to particle movement was obtained. Information relative to total volume movement is less clear. Volume measures of sand and silt transport can be estimated with present techniques.[3] Quantitative measurements are yet to be developed.

Evaluation of Tracer Techniques Applied to Erosion Research

Tracer techniques are not new to erosion research, although the use of radioisotopes has been limited. This review, it is hoped, will arouse interest in new applications of radioisotopes as tracers for characterizing erosion studies.

Advantages of Radioisotopes as Tracers

One of the primary assets of using radioisotopes is the high sensitivity of their detection. The amount of radioactive element present in a normal counting sample is about 10^{-16} to 10^{-19} g. It is possible to detect many common elements at levels of 10^{-11} to 10^{-14} g (Ref. 25). The ultimate sensitivity of radioisotope detection is several orders of magnitude better than optical or electrical conductance procedures.

Measurements of radioactivity can be made in situ and nondestructively. Recent advances in the technique of scintillation counting permit the assay of mixtures of radioisotopes to a degree not previously possible. Nuclear detection devices can be automated easily, and continuous monitoring of radiation activity is entirely feasible.

In general, radioisotopes are cheap, and tagging procedures are not difficult.[7] The cost of most radioisotopes used for tracing experiments seldom exceeds a few dollars per millicurie—some are as cheap as cents per curie. The cost of the radioisotopes is never a limiting factor in any proposed tracer study. Materials used as tracers may be radioactive, or they may be nonradioactive. The latter can be activated by neutrons[28] after the system has undergone reaction. The tracer concentration is then determined by the usual radioactivity measurements.

Possible Disadvantages of Radioisotopes as Tracers

Detection of radioisotopes requires the use of nuclear detection equipment. Even the relatively simple instruments are not cheap, and skilled labor is required to keep them in working order. A considerable range in price parallels the expected performance of the equipment. A portable scaler and scintillation detector might well cost $3000; a laboratory unit of greater precision, $4000. A complete gamma differential scintillation spectrometer will cost from $4000 to more than $15,000. Accessory equipment as well as some laboratory facilities are required for all these systems.

The use of radioactivity in the public domain requires conformity to either AEC or state regulations.

Many tracer experiments can be made using tracers other than radioisotopes. The use of radioisotopes as tracers should not be based on novelty but on superior or unique application.

Application of Research Data

The interpretation of tracer data obtained with radioisotopes is often subject to criticism. The utility of the results may be obscured by many factors. Distance, absorption, change in energy, scattering, self-absorption, counter efficiency, and counter geometry must all be taken into consideration in a measurement of radioactivity. But, even when the measurement is made with a high degree of precision and reliability, the interpretation of the observed radiation intensity may be uncertain.

In erosion research the measurement of volume movement of a soil mass is difficult to evaluate. Materials can be tagged; the added radioactivity can be

located and identified as to source and strength; the distances and times of tracer movement can be measured. If the entire soil mass is known to be traced, or, if the tracer is known to be uniformly mixed in the system sampled, quantitative results can be calculated. These conditions, however, do not usually occur in erosion studies. The resultant tracer data are therefore more qualitative than quantitative. Hubbell and Sayre,[22] Crickmore,[3] and Lean and Crickmore[6] have discussed this problem. It is in this area that further study and development are needed.

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References

References marked with an asterisk were cited by the author but were not available to the Isotopes Information Center for bibliographic verification.

1. G. Courtois, Radioisotopes in Sedimentology (in French), in *Isotopes in Hydrology*, Symposium Proceedings, Vienna, 1966, pp. 117-165, International Atomic Energy Agency, Vienna, 1967. (STI/PUB/141). (An English translation of this paper is available as ORNL-tr-1805.)
2. J. Kohl, R. D. Zentner, and H. R. Lukens, *Radioisotope Applications Engineering*, D. Van Nostrand Company, Inc., Princeton, N. J., 1961.
3. M. J. Crickmore, The Use of Irradiated Sand for Tracer Studies in Hydraulic Models, *La Houille Blanche*, 16: 797-806 (1961).
4. C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes*, 6th ed., John Wiley & Sons, Inc., New York, 1967.
5. J. L. Putman and D. B. Smith, Radioactive Tracer Technique for Sand and Silt Movements Under Water, *Int. J. Appl. Radiat. Isotop.*, 1: 24-32 (1956).
6. G. H. Lean and M. J. Crickmore, Methods for Measuring Sand Transport Using Radioactive Tracers, in *Radioisotopes in Hydrology*, Symposium Proceedings, Tokyo, 1963, pp. 111-131, International Atomic Energy Agency, Vienna, 1963 (STI/PUB/71).
7. J. R. McHenry and L. L. McDowell, The Use of Radioactive Tracers in Sedimentation Research, *J. Geophys. Res.*, 67: 1465-1471 (1962).
8. L. L. McDowell, Sediment Movement as Defined by Radioactive Tracers: A Preliminary Report, in *Proceedings of the Federal Inter-Agency Sedimentation Conference, 1963*, U. S. Department of Agriculture, Miscellaneous Publication No. 970, pp. 550-568, U. S. Government Printing Office, Washington, 1965.
9. A. Gilbert, F. Abecasis, M. Goncalves Ferreira, J. Reis de Carvalbo, and S. Cordeiro, Tracing Undersea Sand Movement with Radioactive Silver, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958*, Vol. 19, 355-359, United Nations, New York, 1959.
10. H. Bougault, A. Caillot, G. Courtois, and B. Jeanneau, Surface Deposition of Radioisotopes on Sands and Silts (in French), in *Isotopes in Hydrology*, Symposium Proceedings, Vienna, 1966, pp. 233-262, International Atomic Energy Agency, Vienna, 1967 (STI/PUB/141).
11. R. Doleyal, M. Petersen, H. Becker, H. Götte, G. Schulze-Pillot, E. Tomschke, B. Böttcher, K. H. Nachtigall, and E. Seibold, Development and Testing of a Radioactive Tracer Method for Measuring the Kinetics of Erosion and Sand Displacement Caused by Surf (in German), Euratom Report EUR-2167.d, 1965.
12. B. L. Campbell, Sediment Research in Australia, *At. Energy Aust.*, 7(4): 13-17 (October 1964).
13. *a. R. B. Krone, Second Annual Report on Silt Transport Studies Utilizing Radioisotopes, USA–Corps of Engineers, Contract No. DA-04-203, CIVENG 58-28, 123 pp., 1959.
    b. R. B. Krone, Third Annual Progress Report on the Silt Transport Studies Utilizing Radioactive Isotopes, USA–Corps of Engineers, Contract No. DA-04-203, CIVENG 59-99, 52 pp., 1960.
14. D. D. Wooldridge, Tracing Soil Particle Movement with Fe-59, *Soil Sci. Soc. Amer., Proc.*, 29: 469-472 (1965).
15. W. S. Ginell and G. P. Simon, Preparations of Tagged Spherical Clay Particles, *Nucleonics*, 11(3): 49-51 (1953).
16. D. B. Smith and T. V. Parsons, Silt Movement Investigation in the Oxcars Spoil Ground, Firth of Forth, Using Radioactive Tracers, 1961 and 1964, British Report AERE-R-4980, 1965.
17. W. J. Price, *Nuclear Radiation Detection*, 2nd ed., McGraw-Hill Book Company, Inc., New York, 1964.
18. G. D. Chase and J. L. Rabinowitz, *Principles of Radioisotope Methodology*, 3rd ed., Burgess Publishing Co., Minneapolis, 1967.
19. C. E. Crouthamel (Ed.), *Applied Gamma-Ray Spectrometry*, Pergamon Press, Inc., New York, 1960.
20. C. W. Sheppard, *Basic Principles of the Tracer Method*, John Wiley & Sons, Inc., New York, 1962.
21. H. W. Feely, A. Walton, C. R. Barnett, and F. Bazan, The Potential Applications of Radioisotope Technology to Water Resource Investigations and Utilization, USAEC Report NYO-9040, Isotopes, Inc., 1961.
22. D. W. Hubbell and W. W. Sayre, Application of Radioactive Tracers in the Study of Sediment Movement, in *Proceedings of the Federal Inter-Agency Sedimentation Conference, 1963*, U. S. Department of Agriculture, Miscellaneous Publication No. 970, pp. 569-578, U. S. Government Printing Office, Washington, 1965.
23. R. B. Curry, Scandium as a Tracer of Movement of Clay Suspensions in Columns of Porous Media, *Amer. Soc. Agric. (English Transl.)*, 9: 88-90 (1966).
24. *Twentieth International Navigation Congress, Section II, Ocean Navigation, Subject 5, Methods of Determining

Sand and Silt Movement Along the Coast, in Estuaries, and in Maritime Rivers. P.I.A.N.O., Brussels, 207 pp., 1961.
25. R. T. Overman and H. M. Clark, *Radioisotope Techniques*, McGraw-Hill Book Company, Inc., New York, 1960.
26. M. H. Frere and H. Roberts, Jr., The Loss of Strontium-90 from Small Cultivated Watersheds, *Soil Sci. Soc. Amer., Proc.*, 27: 82-83 (1963).
27. J. dePloey, Erosion by Rain in the Western Congo (in French), in *Isotopes in Hydrology*, Symposium Proceedings, Vienna, 1966, pp. 291-301, International Atomic Energy Agency, Vienna, 1967 (STI/PUB/141).
28. W. S. Lyon, Jr. (Ed.), *Guide to Activation Analysis*, D. Van Nostrand Company, Inc., Princeton, N. J., 1964. See also R. E. Greene, Tracing with Activable Tracers, *Isotop. Radiat. Technol.*, 5(4): 269-277 (Summer 1968) and 6(1): 70-76 (Fall 1968).

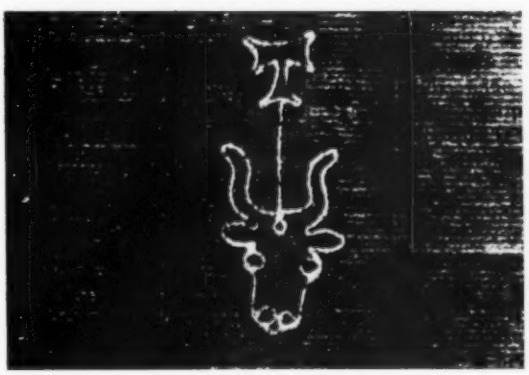
Dating by Beta Radiography*

Radioisotopes are being used to date historic documents in a process similar to X radiography. The method used is *contact beta radiography*, in which a distributed source of low-energy beta radiation in the form of a thin sheet of material is placed on one side of a sheet of paper and a photographic film on the other. The exposure of the film depends on the local "basis weight" (mass/area) of the paper, since this determines the penetration of the beta particles; and the film, when developed, shows not only the low-mass areas of watermarks but also the texture of the paper. This includes, for example, the regular pattern of mass variations due to the supporting wires used in the manufacture of laid paper.

Dating is achieved by examining the features of the picture or pattern represented by the watermarks. Like a trademark, the watermark is different for different paper manufacturers and is changed from time to time. The process is therefore one of historical identification.† The method is particularly good for examining paper in the pages of books, since the beta-emitting sheets and the films can conveniently be placed between the pages without damaging the binding. The resulting radiographs (Fig. 1) showing the watermarks and fine structure of the paper are generally uncomplicated by the printing on the pages, since the mass of this is very small. The method is therefore greatly superior to most optical methods of inspection.

The beta source commonly used is ^{14}C-labeled polymethyl methacrylate, which can be obtained from The Radiochemical Centre, Amersham, Bucks. Exposure time varies with paper thickness, being longer

(a)



(b)

Fig. 1 Beta radiographs of pages from *(a)* Caxton's translation of Ovid's *Metamorphoses* and *(b)* Caxton's *Golden Legend*, ca. 1484. These beta radiographs were made by Dr. Allan Stevenson, at the British Museum.

*Reprinted, with minor editorial changes, by permission from *Atom*, No. 140, pp. 153-155 (June 1968).

†It should not be confused with carbon dating of very ancient documents, like the Dead Sea Scrolls.

for thicker paper. A typical exposure is 15 hr for paper at 6 mg/cm^2 (the thickness of a sheet of newspaper), using a ^{14}C–plastic sheet containing 80 μc/g. The necessary exposure will be doubled for each additional 2 mg/cm^2 of thickness but will also be inversely proportional to the specific activity of the sheet. The Radiochemical Centre also supplies sheets of higher specific activity.

The method involves no radiation hazard.

(MG)

Nuclear Weighing Devices

By Martha Gerrard

Abstract: *Patented devices that continuously determine the weight of bulk material on a moving conveyor belt by measuring transmitted radiation are described, together with a device that uses the same principle to weigh coal in moving cars.*

The Isotopes Information Center has been asked several times recently for a description of continuously operating nuclear "scales," i.e., nuclear weighing devices, for use with moving objects. Such devices, which have been patented[1] and may be purchased from commercial suppliers,[2,3] determine the weight of a bulk substance by measuring the fraction of incident gamma radiation transmitted by the substance and converting this value to weight. The scale is really a modification of the well-known thickness and density gages, which measure weight per unit area, i.e., the product of density times thickness, and thus determine density at constant thickness or thickness at constant density. Some of the advantages of the nuclear scale are that it makes no contact with the material being weighed and that it can be used to weigh material on vibrating-apron, drag-chain, belt, or air-slide conveyors up to 6 ft wide or to control weigh feeders. Having no moving parts, it can be used in dusty or corrosive atmospheres. The weighing is a continuous procedure, and weights are read directly from electronic printouts. The device can be installed easily and rapidly on existing conveyors.

Description of Nuclear Scale

A commercially available nuclear weighing device for use with material on a conveyor belt consists of a steel C-shaped tube. The lower section of the C contains a strip radioisotope source—^{137}Cs—shielded in lead; the top section contains a radiation detector, which is a series of cells arranged in a row parallel to the source strip. The conveyor belt passes between the top and bottom sections (Fig. 1*a*). The radiation-detector response varies with the amount of material that passes between it and the source, and the "amount" value registered by the detector is multiplied, in the recorder unit (Fig. 1*b*), by belt speed to give mass flow rate, or weight per unit time. Because the entire belt width is exposed to the radiation, variations in width, density, or thickness of the material being weighed do not affect the results. A tachometer is provided to indicate belt-speed variations of more than, say, 0.5%.

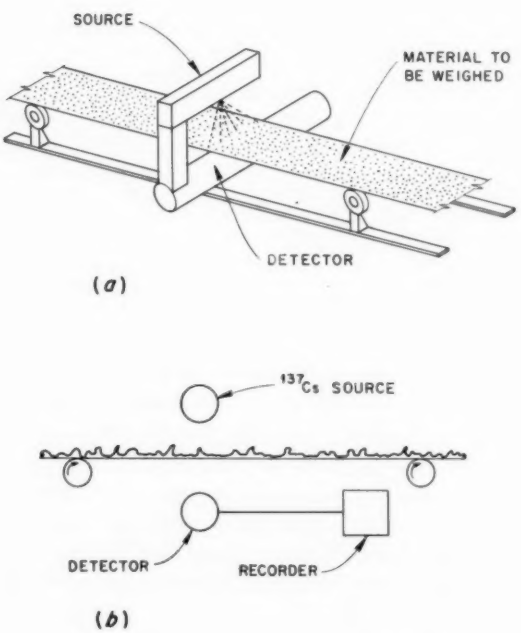


Fig. 1 *(a)* **Nuclear scale in position to weigh material on a conveyor belt and** *(b)* **cross-section diagram of the nuclear scale.**

Performance of Nuclear Scale

Reports[4-6] on the performance of a nuclear weight gage tell of its use to weigh cement clinker in the vary dusty atmosphere of a tunnel. Mechanical weighing units had not been successful under these conditions,

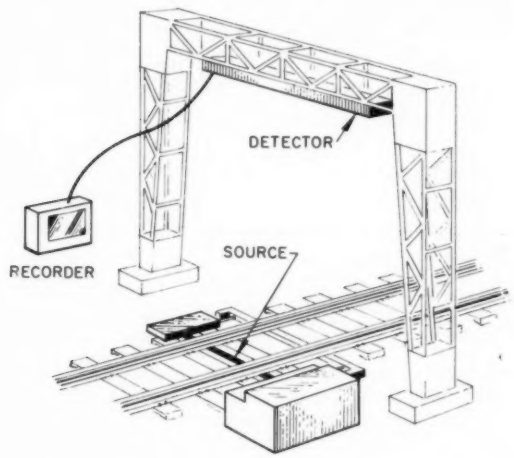


Fig. 2 Source–detector arrangement for determining weight of coal in moving railroad cars.

but the nuclear gage weighed the clinker with a precision of better than ±1%. In several other cement plants, the gage was used for automatic control of delivery of material via an air slide. In a potato warehouse, operating 6 or 7 days/week for 24 hr/day, the gage weighed potatoes accurately at a rate of 30 tons/hr. Formerly the produce had been weighed in individual tote boxes, a slow and laborious procedure. Wood chips, coal, and phosphate mud and rock have also been weighed with the device.

In a Polish test[7] of a prototype scale of this kind, zinc–lead ore was weighed with an error of about ±5%. The radiation source used was ^{60}Co. The experimenters felt that many changes could be incorporated in a final model which would improve the accuracy. The Russians[8] have a scale of this kind that uses ^{90}Sr.

The same principle on which the conveyor-belt scale is based is used also as the basis for a device for weighing coal in railroad cars (Fig. 2), for example.[9] Here the track on which the car moves passes between the radiation source and detector, and the coal is weighed as the car is moving.

References

1. P. E. Ohmart, Method and Apparatus for Continuously Weighing Material on a Conveyor Comprising a Radioactive Source and Detector, U. S. Patent 3,278,747, Oct. 11, 1966 (filed July 29, 1963); Improvements in and Relating to Measurement of Material on a Conveyor, British Patent 1,078,831, Aug. 9, 1967.
2. Ohmart Corp., 4241 Allendorf Drive, Cincinnati, Ohio 45209, Bull. Nos. BW-1 and WFS.
3. Nuclear Chicago, 9101 Highway 183, P.O. Box 9267, Allandale Station, Austin, Tex. 78756.
4. S. Rowe, Nuclear Continuous Weighing Scale for Solids on Conveyors, Preprint from Instrument Soc. Am., Chicago, 1963, CONF-147-6 (*Nucl. Sci. Abstr.*, 18: 2013).
5. S. Rowe, Nuclear Weighing, *Instr. Control Systems*, 40(2): 85-86 (1967).
6. R. J. Bierman, address at 51st National Conference on Weights and Measures, Denver, July 1966; summarized in Weighing Arrangements—A Systems Review, *Eng. Mining J.*, 168(6): 186 (1967).
7. J. Girczys and A. Piatkowski, Industrial Tests of an Isotope Belt Conveyor Balance (Polish), *Rudy Metal Niezelaz.*, 12: 359-362 (1967).
8. R. Kaluta and A. Pruzki, Use of Isotopes as Sensing Elements for the Automation of Measuring of Weighed Materials (Polish), *Pomiary Automat. Kontr.*, 1967(1): 23-26.
9. J. J. Wright, Radioactive Weighing System for Moving Vehicles, U. S. Patent 3,132,247, May 5, 1964 (filed Nov. 2, 1959). [Abstracted in *Isotop. Radiat. Technol.*, 6(2): 225 (Winter 1968–1969).]

New Publications on Standards

The Subcommittee on Use of Radioactivity Standards of the National Academy of Sciences, National Research Council, has recently published[1,2] a recommendation of two reports for users of standards. These publications are being distributed to commercial suppliers of solution standards and are available to other interested parties from the address given below.

Certificates of Radioactivity Standards[3] is intended to provide a model certificate that is sufficiently informative and precise to meet various users' needs.

To fill out the model certificate requires, for each radionuclide, information on the chemical and physical properties, method of production and standardization, magnitude and sources of errors, and the decay scheme on which standardization is based. Hopefully, the model certificate will encourage commercial suppliers to include similarly detailed information in their own certificates for radioactivity standards and by this means to distinguish between standards and approximately calibrated solutions.

The Users' Guides for Radioactivity Standards[4] is a collection of one-page discussions of possible chemical and counting problems for each of 40 radionuclides. Properties such as radiocolloidal behavior, volatility, genetic relations, and decay by several modes of radiation are described. The guides were written for both users who are unfamiliar with these problems and users who need to be reminded of them; they are intended to emphasize the most important problems, and they refer the reader to more detailed presentations of the chemical and nuclear decay properties of the radionuclide.

The Subcommittee welcomes comments, additions, and corrections concerning these publications and also suggestions for other activities to aid users of radioactivity standards. These, and requests for copies of the publications, should be addressed to: Subcommittee on Use of Radioactivity Standards, National Academy of Sciences, National Research Council, 2101 Constitution Avenue, Washington, D. C. 20418.

(FEM)

References

1. International News, *Int. J. Appl. Radiat. Isotop.*, 19: 603 (1968).
2. Aids for Users of Radioactivity Standards, *Health Phys.*, 15: 99 (1968).
3. S. B. Garfinkel, A. P. Baerg, and P. E. Zigman, Certificates of Radioactivity Standards, National Academy of Sciences, National Research Council, Washington, 1966.
4. B. Kahn, G. R. Choppin, and J. G. V. Taylor, Users' Guides for Radioactivity Standards, National Academy of Sciences, National Research Council, Washington, 1967.

Man-Made Radioisotope To Aid in Search for Minerals, Oil, and Groundwater

The artificial radioisotope ^{252}Cf is expected to aid significantly in locating mineral and oil deposits and sources of groundwater. In recent experiments at the Atomic Energy Commission's Savannah River Plant (SRP) in South Carolina, scientists of the U. S. Geological Survey used a 100-μg source of ^{252}Cf in a capsule the size of a pencil eraser to detect small pieces of gold and silver ore that had been implanted at shallow depths below the ground surface. The californium was produced in a nuclear reactor at the SRP and further refined in cooperation with the AEC's Oak Ridge National Laboratory.

By the neutron activation technique, and using this source, gold at concentrations of only 0.3 oz/ton and silver at 1.5 oz/ton were detected. The source was also used successfully to detect rare earths in phosphorite samples from the Bone Valley formation near Barstow, Calif., and in geologic test wells down to 1100 ft at the SRP to make a continuous log of the well. This type of log indicates rock-strata water components in the well even behind the thick iron casing of the well hole, and the technique is potentially useful also for locating pockets of oil in the earth.

Because of its small size and relatively maintenance-free aspects, scientists predict that ^{252}Cf may be used in locating mineral deposits on the ocean floor, in industrial quality control and on-line analysis, in analyzing materials of the moon's surface, and in upgrading of gold, silver, or other valuable mineral ores. At least 30 other elements are amenable to exploration with this source, including U, V, Cu, Al, F, Sn, Si, Na, and Fe. The neutron activation technique is not new, but the ^{252}Cf source may quite possibly provide a breakthrough in the miniaturization of irradiation equipment, since it could reduce the size of a probe by a factor of 10^5

Doctors have also shown an interest in ^{252}Cf for cancer therapy and to improve radiographic techniques.

(From USAEC News Release No. L-182, Aug. 6, 1968.) (MG)

Improved ^{124}Sb–Be Source Provides Intermediate Flux of Thermal Neutrons

Atomic Energy of Canada Limited (AECL) has introduced two commercially available neutron activation analysis facilities*,†—a large-volume irradiation facility (Fig. 1) capable of holding up to 12 pencils of ^{124}Sb around a central cavity having a volume of ~20 cm^3 and a completely self-contained

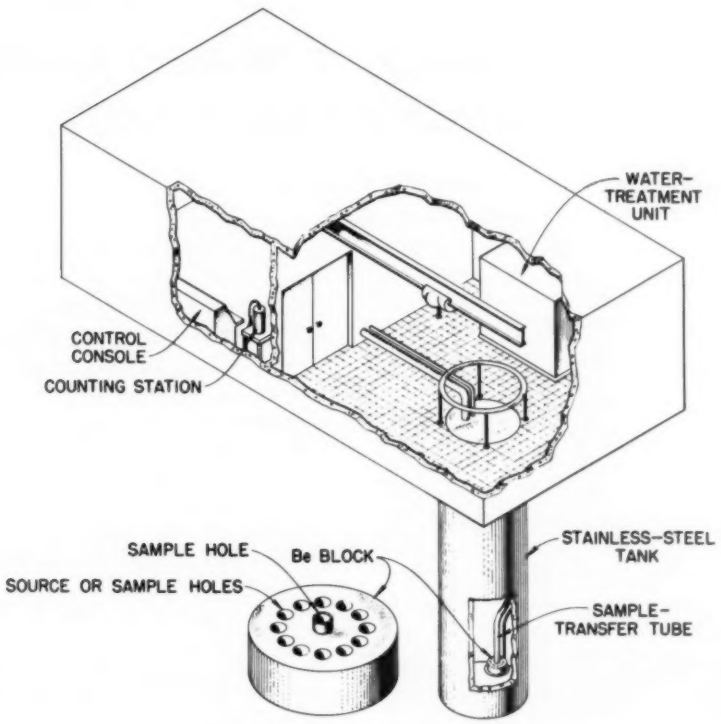


Fig. 1 Neutron pool facility.

mobile or laboratory facility—for precision analysis (±1%) and short-lived tracer production (90 radioisotopes with half-lives from 1 sec to 200 min and with specific activities ≥0.1 μc/g). AECL claims that the ^{124}Sb source(s) placed in a newly designed beryllium block provides a most economical (~$15,000 for the mobile or laboratory facility and ~$40,000 for the large-volume facility exclusive of building and pool) source of intermediate fluxes of thermal neutrons [1 x 10^8 n/(cm^2)(sec)]. (JEC)

*W. E. Downs, A ^{124}Sb–Be Source of Thermal Neutrons for Precision Analysis and Tracer Production, *Nucl. Appl.*, 5(2): 55-61 (1968).

†C. Law, Work-Horse Neutron Source, *Can. Res. Develop.*, 38-40 (1968).

Section
III
Isotopes and Radiation Technology

Applications in Life Sciences

Fluorescent Scanning: A Medical Application of Fluorescent Spectroscopy

By Paul B. Hoffer, M.D.*

Abstract: *X-ray fluorescence has been used in organ scanning, producing images of the organs studied, by using the radiation from a ^{241}Am source. Examples are presented of thyroid and liver scans produced with a "fluorescent scanner."*

Virtually all applications of diagnostic radiology in medicine are built around a single fundamental property—the fact that different materials exhibit differential absorption of X rays. For example, because bone is dense and contains large amounts of calcium, it can be easily distinguished from surrounding soft tissues or air in routine radiography. However, the radiograph is fairly crude as a system of physical or chemical analysis, and only relatively large differences in absorption can be distinguished. This accounts for the apparent paradox that, although iodinated compounds are used in radiology to visualize various other organs of the body, the thyroid gland, which is the natural "reservoir" for iodine and usually contains approximately half of the body's iodine supply, cannot be seen on radiographs. Iodine must be present in a concentration of 2% or more before an organ can be visualized on a routine diagnostic X-ray film. The thyroid gland contains 0.04% iodine and is therefore radiographically "invisible."[1]

The demonstration of small concentrations of elements in body tissues has long been a challenge to research radiologists. Jacobson, Edholm, MacKay, Heedman, Roy, and others have been able to demonstrate small concentrations of iodine in phantoms and in human subjects by using the concept of dichromography.[2-6] Unfortunately, the elaborate equipment required for these studies tends to relegate the technique to the experimental laboratory.

Our technique for imaging the thyroid gland incorporates the basic scheme of an X-ray fluorescent spectrometer.[7] The equipment is a modification of TMC Model 331 Photon Spectrometer used in conjunction with a ^{241}Am source. Figure 1 shows a diagram of the source and detector array.† The entire unit is mounted on the probe of a commercial medical rectilinear scanner, which is normally used for imaging the thyroid with nuclides such as ^{131}I or ^{125}I.

Americium-241 is used as the radiation source because it produces a reasonably monochromatic 59.57-kev gamma ray (for each 100 alpha disintegrations, ^{241}Am emits 36 gamma rays at 59.57 kev and smaller numbers of gamma and X rays at energies less than 26.36 kev; all the alpha particles are either self-absorbed or absorbed in the encapsulating material).[8] This energy is above the K-shell edge of iodine, which is 33.2 kev, and is also high enough above the characteristic radiation of iodine not to interfere as background. When the 59.57-kev source X ray interacts with a K-shell electron in the iodine atom, a photoelectron is produced and a vacancy is created in the K shell. An electron falls from one of the outer shells to replace it, and a characteristic X ray is produced. The probability that this will occur is 87%. When the

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†The figures in this paper appeared in a paper, Fluorescent Scanning: A New Investigative Technique, presented by P. B. Hoffer et al. at an IAEA Symposium on Medical Radioisotopic Scintigraphy, Salzburg, Austria, Aug. 6–15, 1968. The conference proceedings are in press.

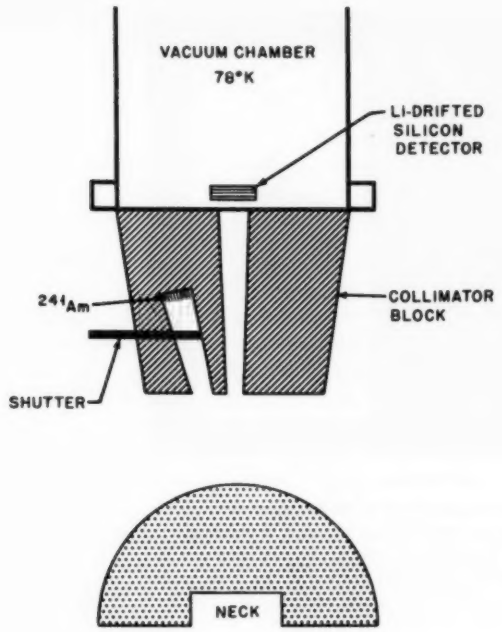

Fig. 1 Schematic representation of the source–detector section of the fluorescent scanner.

electron is from the L shell, the 28.5-kev K_α characteristic X ray is generated; and, when the X ray is from the M shell, the 32.3-kev K_β characteristic X ray is produced.[9] Production of K_α X rays predominates over production of K_β X rays in a ratio[10] of approximately 7.5 to 1. It is the K_α X ray with a half-value layer in soft tissue of approximately 2 cm which is used to produce the thyroid image in this system. The detector is a 30-mm^2 lithium-drifted silicon crystal with a depleted layer of 3 mm. The energy resolution of this crystal for energies in the neighborhood of 30 kev is better than 500 ev full width at one-half maximum at 78°K. The efficiency of collection is approximately 66%.

We have been able to use this system for producing thyroid scans in humans (Fig. 2). The scans resemble routine isotope scans, but have a higher "background," and the dose to the patient is significantly lower. The fluorescent thyroid scan requires a dose of about 200 mrads, compared to the 5- to 25-rad dose (possibly higher) from routine ^{125}I or ^{131}I scans.[11]

The potential of this technique seems particularly exciting because it adds a unique parameter to thyroid imaging. The fluorescent scan will provide information about the distribution of iodine in the thyroid, although it gives only indirect information about the gland function. As a result, its value may prove to be greatest when it is used in conjunction with conventional methods of scanning. A battery of images produced by technetium (as the pertechnetate), radioiodine, and fluorescent scans would thus provide information about thyroid trapping, hormone function, and overall iodine distribution. It is even possible that fluorescent scans of "cold" nodules might show differences in iodine distribution which would be characteristic enough to permit accurate diagnosis of the various etiologies possible for these lesions.[12,13]

The fluorescent scanning technique can be used to mimic certain radioisotope studies without the use of radioactive isotopes. An inert tracer can be given to the patient and allowed to concentrate in a selected organ and the organ then scanned with the fluorescent

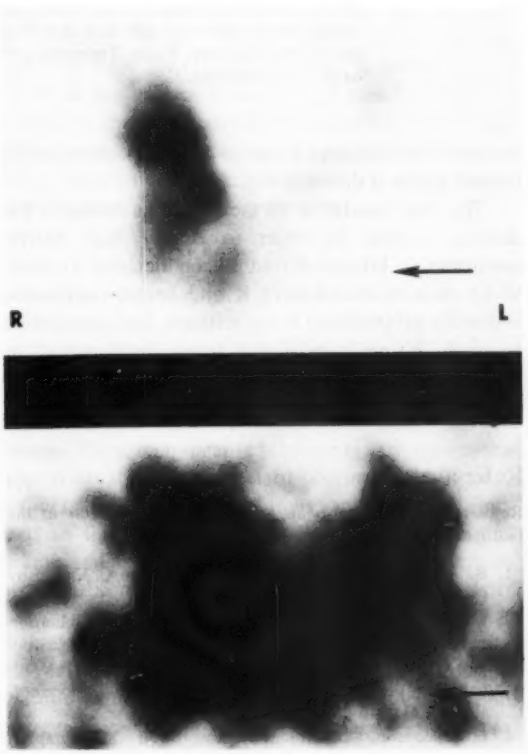

Fig. 2 Scans of thyroid gland showing an abscess (pointed to by arrows) in the left lower pole. The upper scan was made on a conventional scanner using ^{131}I, and the lower figure was produced with the fluorescent scanner. The abscess was verified at surgery.

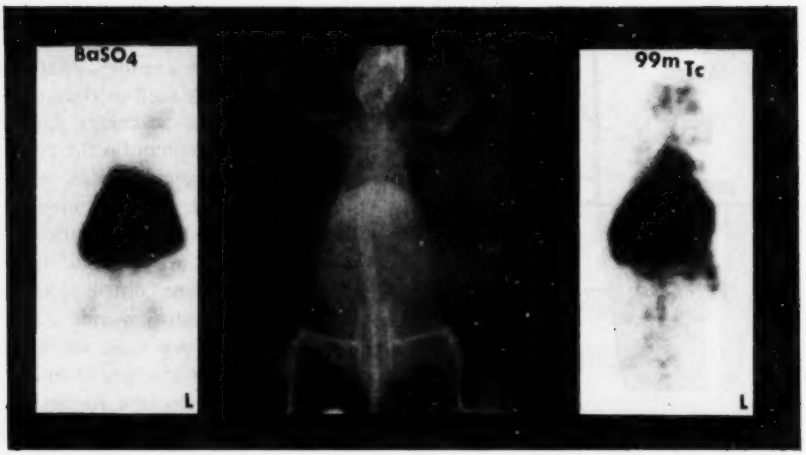

Fig. 3 Fluorescent scanning using a nonradioactive tracer. Left: Fluorescent scan of a mouse injected with colloidal barium sulfate (average particle size 0.35 μ). The liver is well demonstrated. Middle: Radiograph taken immediately after the fluorescent scan. The concentration of barium in the liver and spleen is insufficient to permit good visualization of the organ with this 45-kvp exposure. Right: Technetium-99*m* sulfur-colloid scan on the same animal (2 weeks later) for comparison.

scanner to produce an image of the organ. An example of such a scan is shown in Fig. 3.

The chief limitation of the technique to date is the detector crystal. In order to achieve high energy resolution, a lithium-drifted silicon detector is used, which must be cooled to 78°K; and, because resolution is directly proportional to capacitance, the crystal must be small. We are hopeful that future developments in the field of solid-state detectors will help to alleviate this problem.[14] (MG)

References

References marked with an asterisk are not available at the Isotopes Information Center.

1. B. A. McGavack, *The Thyroid,* p. 53, The C. V. Mosby Company, St. Louis, Mo., 1951.
2. P. Edholm and B. Jacobson, Quantitative Determination of Iodine in Vivo, *Acta Radiol.*, **52**: 337-346 (1959).
3. P.-A. Heedman and B. Jacobson, Thyroid Iodine Determination by X-Ray Spectrophotometry, *J. Clin. Endocrinol. Metab.*, **24**: 246-252 (1964).
4. *B. Jacobson, Dichromatic Absorption Radiography, Dichromography, *Acta Radiol.*, 39: 431-452 (1953).
5. *R. S. MacKay, X-Ray Visualization and Analysis Using Spectral Information, *IRE Trans. Med. Electron.*, ME-7, 77-99 (1960).
6. O. Z. Roy, R. A. Beique, and G. L. D'Ombrain, A Method of Iodine Determination by Characteristic X-Ray Absorption, *IRE Trans. Bio-Med. Electron.*, ME-9, 50-53 (1962).
7. P. B. Hoffer, W. B. Jones, R. B. Crawford, R. N. Beck, and A. Gottschalk, Fluorescent Thyroid Scanning: A New Method of Imaging the Thyroid, *Radiol.*, **90**: 342-344 (1968).
8. *K. H. Hyde, H. R. Bowman, and D. H. Sisson, Analytical Capabilities of a Semiconductor X-Ray Emission Spectrometer, Report UCRL-16845, 1966.
9. *H. E. Johns, *The Physics of Radiology,* 2nd ed., p. 611, Charles C Thomas, Publisher, Springfield, Ill., 1961.
10. G. L. Clark, *The Encyclopedia of X Rays and Gamma Rays,* pp. 1124-1135, Reinhold Publishing Corporation, New York, 1963.
11. E. M. Smith, G. L. Brownell, and W. H. Ellett, Radiation Dosimetry, in *Principles of Nuclear Medicine,* pp. 742-784, Henry N. Wagner, Jr. (Ed.), W. B. Saunders Company, Philadelphia, 1968.
12. G. A. Medeiros-Neto, W. Nicolau, J. Kieffer, and R. R. Pieroni, Insoluble Iodoprotein in Thyroid Nodules, in *Current Topics in Thyroid Research,* Proceedings of the 5th International Thyroid Conference, Rome, 1965, pp. 910-919, C. Cassano and M. Andreoli (Eds.), Academic Press Inc., New York, 1965 (CONF-65/05/51).
13. *R. Pitt-Rivers and J. R. Tata, *The Chemistry of Thyroid Diseases,* pp. 54-66, Charles C Thomas, Publisher, Springfield, Ill., 1960.
14. J. F. Tinney, Lawrence Radiation Laboratory, personal communication, May 31, 1968.

Recent Advances in Scanning*

By P. V. Harper, Jr., A. Gottschalk, and R. N. Beck†

Abstract: *The status of the art of scanning in medical diagnosis is presented. The factors important in scanning, such as pharmaceutical agents and isotopes, scanners, and pathological conditions, are discussed both individually and interdependently.*

During the past several years, there has been a rapid development in what might be described as the cultural background of scanning, with the result that the simple question, "Which scanner should I buy?", now calls for highly sophisticated and somewhat conflicting answers in a substantial variety of scientific fields. The term "scanning" has come to include the use of stationary as well as moving devices with their rather different descriptive parameters, but the recent use of stationary cameras as moving scanner heads certainly reduces the possibility of considering separately such types of apparatus. The growing popularity of short-lived radioisotopes as scanning agents has greatly increased the flux of available useful photons and, together with the increased sensitivity of camera heads, has resulted in an increase of available count rates of as much as two orders of magnitude. In fact, in some cases the photon fluxes used in diagnostic radiology with image intensifiers now exceed those used in scanning by a factor of only 100. This has led to the extension of image analysis methods currently used in radiography to include radioisotope scans and to the substitution of the concept of modulation transfer for that of spatial resolution. Statistical criteria of merit for the comparison of performance of different scanning systems have been developed by several investigators, and there is a much deeper understanding of the numerous factors involved in the interactions of the emitted gamma radiation within the source, the collimator, and the crystal detector. In addition, criteria for optimizing pulse-height analysis are now better understood. A great variety of methods for processing the final images are under active investigation. Several scanning modes that differ from the conventional rectilinear approach have been proposed, usually with a view to securing improved insight into the three-dimensional distribution of the radiation source. The possibilities of scanning with positrons are again receiving close scrutiny because of their capabilities along these lines and because of the increasing availability of short-lived positron emitters. The use of particulate carriers for radioisotopes has opened up a whole new field in perfusion scanning and visualization of the reticuloendothelial system. Considerable dividends have already accrued from many of these factors in routine nuclear medicine procedures, particularly in liver, brain, and lung visualization. The present status of many of the problems of scanning has been well presented in recent symposia[1-5] and has been reviewed by Mallard,[6] Beck,[7] Anger,[8] and McAfee.[9] In this paper we have attempted to convey a feeling for the "state of the art" of scanning, and considerations are limited to more or less editorial remarks on the ideas and proposals that appear to the authors to point to future developments and to areas in which major questions seem to remain unanswered.

Important Factors in Various Scanning Situations

The object in scanning is to collect the most information about the isotope distribution within the patient in the least time, with the least radiation dosage. These reciprocal requirements vary from situation to situation with different pharmaceutical agents, scanners, pathological conditions, and radiation emitters, so that partial comparisons on an other-things-being-equal basis, while sometimes necessary, have on occasion been misleading. It would appear desirable to consider all the above factors in the complete system in making a comparison between systems. The question thus becomes very complex, since one has to consider the optimal crystal size and configuration, collimation, energy, pulse-height analysis, and image presentations, as well as isotope distributions and deposition in the patient.

Many of these factors are strongly interdependent and must be lumped together. For instance, the energy of the emitted gamma ray determines the spectral shape of radiation scattered from the patient's body. It

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also determines the material and thickness of the collimator and the septum thickness between holes. The crystal thickness should be sufficient to absorb most of the radiation, and its shape should ensure good light collection; that is, its thickness should be equal to or less than its diameter. The shape of the crystal also determines what fraction of the incident radiation is absorbed and what fraction of the radiation originating in the crystal escapes from the crystal—i.e., the relative probability of an incident photon producing a scintillation lying in the photopeak. Pencil-like crystals such as those used in the autofluoroscope have good absorption of the incident gamma radiation, but many of the Compton photons arising in the crystal escape from the sides. The broad thin crystal of the scintillation camera, on the other hand, has less complete gamma absorption but much better absorption of the scattered Compton photons so that, rather surprisingly, the number of possible photopeak events is approximately the same for both crystals over a wide energy range. The cathode of the photomultiplier tube should be as efficient as possible, so that the statistical degradation of the energy resolution will be minimized. By using pulse-height analysis, the region of the photopeak is separated from the overlapping scatter spectrum as completely as possible. If all scattered radiation is considered to be undesirable noise that increases the background of the record, it is simple to devise an optimal setting for the lower discriminator to divide the overlapping scatter and photopeak regions and to give a minimal statistical error. It would appear that photons scattered through a small angle are not completely devoid of information about their origin, and it is, in fact, these photons which are in the high-energy end of the scatter spectrum overlapping the photopeak. Thus, in effect, the pulse-height analyzer acts in a sense to vary the field of view of the collimator, admitting scattered photons from wider angles as the lower discriminator is lowered. This effect, however, is insignificant in a practical sense, since measurements of modulation transfer in a scattering medium lead to virtually the same optimal pulse-height analyzer settings as when all the scattered radiation is considered to be noise. The use of bialkali phototubes, which considerably increases the number of effective primary photoelectrons per scintillation event in the crystal, should lead to a substantial improvement in this area by sharpening the energy resolution and permitting better pulse-height analysis.

Background caused by photons penetrating the septa has been limited arbitrarily in collimator design to about 10% of the total observed counting rate. Treatment like that used in the scattered-radiation studies leads to approximately the same figure in considering septal penetration of focused collimators, where the entire field of view of the collimator (with and without septa) is for the most part covered by the object being scanned. In collimators for nonmoving systems such as the Anger camera, where the region from which penetrating gammas may originate is often enormously greater than the region being scanned, the 10% criterion applied to focused collimators appears to be too stringent, and, since perfectly adequate pictures may be obtained with much higher penetration fractions computed in the usual way, it is clear that some other parameter must be devised to optimize the septum penetration in this situation.

Short-Lived Radioisotopes

As mentioned above, interest in short-lived emitters has increased greatly during the past few years. These agents have several advantages, since the millicurie quantities that can be administered reduce the time necessary for scanning and thus permit studies on very ill patients who would be quite unable to cooperate for the time required by the longer-lived agents. Additional gains are the possibilities of repeating studies and taking scans from many directions without extending the time of the examination too greatly.

The availability of short-lived emitters has also increased recently. This is due largely to the development of generators or "cows." The first of these, the ^{132}Te generator, gives rise to ^{132}I, which unfortunately has much too high a gamma energy for practical collimation and thus is of no use in scanning.

On the other hand, ^{99}Mo, with a 2.7-day half-life, gives rise to the 6-hr ^{99m}Tc, which has ideal physical characteristics for scanning—a clean 140-kev gamma, which is only about 10% converted, and no primary particle radiation. Thus the energy deposition in tissues per useful emitted photon is very small. Biological properties of technetium have proved to be quite flexible. As pertechnetate, which is the most easily available form, it behaves rather like I^-, being concentrated in the thyroid, salivary glands, and stomach and being initially distributed in the extracellular space. It is thus useful for brain and thyroid scanning. When reduced to a lower valence state, it combines with albumin and may be used for blood-pool scanning and for perfusion scanning after heat coagulation. Several methods are in use for preparing ^{99m}Tc as a colloid for reticuloendothelial-system scanning; and, when combined with iron in the presence of ascorbic acid, it

makes an excellent agent for kidney scanning. In addition, it appears possible to label erythrocytes with this emitter. As a result of these properties, ^{99m}Tc is rapidly becoming a most popular scanning agent, particularly for the brain, since 10- to 15-mc quantities may be administered without undue irradiation to the patients.

Strontium-87*m* the 2.8-hr half-life daughter of ^{87}Y, is likewise available as a short-lived agent for bone scanning and replaces 65-day ^{85}Sr. The 1.7-hr ^{113m}In, daughter of 112-day ^{113}Sn, appears to be useful, and its capabilities are being explored in several laboratories. The 58-min ^{68}Ga, positron-emitter daughter of 275-day ^{68}Ge, is also being actively investigated as a scanning agent, particularly when carried on hydrous ferric oxide. This material, commonly used in radiochemistry as a scavenging agent for many carrier-free radioisotopes, can, under proper conditions, form colloids of different sizes, which have useful biological properties. The very small particles circulate for many hours, larger particles are phagocytized by the reticuloendothelial system, and particulate aggregates are trapped in the lungs. In addition to ^{68}Ga, both ^{113}In and ^{99m}Tc have been prepared as ferric oxide sols.

For those with ready access to reactors or accelerators, several other short-lived agents are available, particularly ^{18}F for bone scanning. Because of the many demonstrated advantages of using short-lived isotopes, considerable interest is developing in such isotopes as ^{38}K, ^{30}P, ^{11}C, and ^{13}N. A small (30 in.) sector-focused cyclotron of reasonable cost is actually being produced commercially with this type of application in mind.

Scanners

Collimator Resolution. A number of unresolved questions remain, however, concerning the most efficient manner in which the various parts of the system should be put together. By specifying many of the conditions of a scanning situation, e.g., crystal size; tumor size, depth, and thickness; uptake of isotope; gamma energy; and collimator material, resolution, and permitted penetration fraction (i.e., fractional increase in count rate due to penetration of the collimator septa by gamma rays), it is possible to design the most efficient collimator for this one situation. Unfortunately this collimator will not be the best for all scanning situations. In fact, such collimators designed for low and intermediate gamma energies typically accept radiation from a rather large solid angle so that there is reduced depth of focus. Various restrictions have been introduced in collimator design to take account of this problem of producing the desired field of view. In one direction, long-focal-length collimators with a small solid angle of view have been used, sometimes in opposing pairs to give great depth of focus; the resultant loss in geometrical efficiency is made up by using multiple detector heads. In the other direction, very large solid-angle detectors have been made which have resulting high efficiency and good depth resolution, allowing rapid multiple scans to be done in various planes. A recent extremely ingenious proposal by Anger disposes of the problem by making use of a large solid-angle collimator backed by a scintillation camera. Objects outside the focal point of the collimator then appear to move across the crystal face in the direction of the scan motion, those at the focus are seen uniformly by the crystal, and those inside the focus appear to move across the crystal in the opposite direction. By simple mechanical and optical means in the readout, this information in each plane can be brought into focus, thus producing simultaneous body-section scans at all depths. At the present time, the practical solution seems to be to try to choose the appropriate collimation for the particular region of interest. The basic advantage of the focused collimator is that its best resolution is some distance in front of the collimator face so that in situations where the region of interest is well known, as in the thyroid, or deep below the surface, as in the brain, this type of collimator will give the best results. Parallel-hole collimators as used in cameras, on the other hand, have their best resolution at the collimator face so that in the liver, for example, where front, back, and side views of the organ may be obtained in a reasonable time with a camera, a large portion of the organ is viewed where it is near the surface of the body and in the region of good resolution. The use of larger 2- by 5- or 2- by 8-in. crystals in scanners must be viewed in context with the desired collimator field of view. Large crystals of this sort would seem to have the most promise in scanning with higher energy emitters where thicker, heavier collimators backed by correspondingly larger crystals to preserve the desired shape of the field of view are needed. In the other direction, much smaller 0.25- by 1.5-in. crystals with thin collimators containing many small holes may be designed to give the same field of view when scanning with lower energy emitters.

In considering optimum resolution, it must be recognized that, while sharpening the focus of a collimator allows one to localize activity with much more certainty, at least in the plane of focus, the

sensitivity of the collimator decreases approximately as the square of the diameter of the field of view at the focus when the crystal size is held constant. Thus the count rate rapidly becomes so low that either the scan time is greatly prolonged or the quantity of isotope must be greatly increased. Just where to compromise in this situation is not clearly resolved. It is possible by setting arbitrary limits on scanning time, area scanned, and isotope (or radiation) dosage to arrive empirically or theoretically at a resolution that will give minimum statistically valid count-rate differences between adjacent target and nontarget regions in the available time. Thus the minimum diameter of an object that can be detected under these boundary conditions is defined (and, as a corollary, the best usable resolution). This is the figure-of-merit approach. Basically the figure of merit is defined as follows: Let C_t and C_0 be count rates over adjacent regions, each viewed by the collimator for time τ. The accumulated counts are $C_t\tau$ and $C_0\tau$, respectively. The difference in these numbers has an associated standard deviation $\sqrt{C_t\tau + C_0\tau}$. A measure of the statistical reliability of this difference is the number of standard deviations, Z, of the difference contained in the difference, thus:

$$Z = \frac{C_t\tau - C_0\tau}{\sqrt{C_t\tau + C_0\tau}}$$

rearranging,

$$\tau = \frac{Z^2(C_t + C_0)}{(C_t - C_0)^2}$$

In a more efficient system, or one in which the difference $C_t - C_0$ is greater, τ will be shorter; thus $1/\tau$ is a measure of the merit of the system. For convenience the figure of merit, Q, is defined as Z^2/τ; and, if errors of the first and second kind are considered (i.e., C_t and C_0 are different, when in fact they should be the same, and vice versa), a factor of 4 is introduced into the numerator. Figure 1 indicates how the various physical parameters enter into the computation of the figure of merit.

For comparing systems of equal resolution, the figure of merit serves admirably. For realistic boundary conditions, this criterion implies that the optimum gamma energy for detecting, for instance, a brain tumor in the center of the head is between 100 and 200 kev. The losses due to absorption in tissue as the energy is reduced from higher values are more than made up by improved detector and collimator efficiency. The increasing scatter with lower energy gammas has not proved to be as disturbing as originally thought, so that even ^{197}Hg, with principal radiation in the 60- to 80-kev range, is proving quite useful. In making comparisons such as this, it must always be remembered that a factor of 5 in a physical parameter may well be offset by a factor of 50 in a biological or dosimetric parameter when the figure of merit is normalized to equal radiation dosage to the target organ.

The difference between the target and nontarget regions, sometimes presented as the target–nontarget ratio C_t/C_0, may also be expressed as

$$m_i = \frac{C_t - C_0}{C_t + C_0}$$

which defines the "modulation" (the subscript i referring to the image). This allows the variations in count rate in a scan to be treated in a manner strictly analogous to electrical signals, and, if the modulation is thought of as a sort of contrast, a system that degrades this contrast least compared to the original isotope concentration (having modulation m_0) would appear to have the best "resolution." The degree of contrast that is preserved or "transferred" when scanning objects of progressively smaller size is described by the modulation transfer function (MTF), defined as:

$$\text{MTF} = \frac{m_i}{m_0}$$

Large objects covering the entire field of view of the collimator give full contrast, or MTF = 1, while narrow objects give lower values. Conventionally the standard test object is a sine-wave distribution of activity of varying spacing or frequency, and the variations in count rate, expressed as modulation, are plotted against space frequency to define the collimator response. The same information may be obtained easily from the collimator response as it moves across a linear source by simple Fourier transformation of the "line spread function." This provides a useful, simple reproducible test object which, together with the sensitivity, completely describes the collimator response in the focal or any other plane.

The figure of merit

$$Q = \frac{(C_t - C_0)^2}{C_t + C_0}$$

and the image modulation

$$m_i = \frac{C_t - C_0}{C_t + C_0}$$

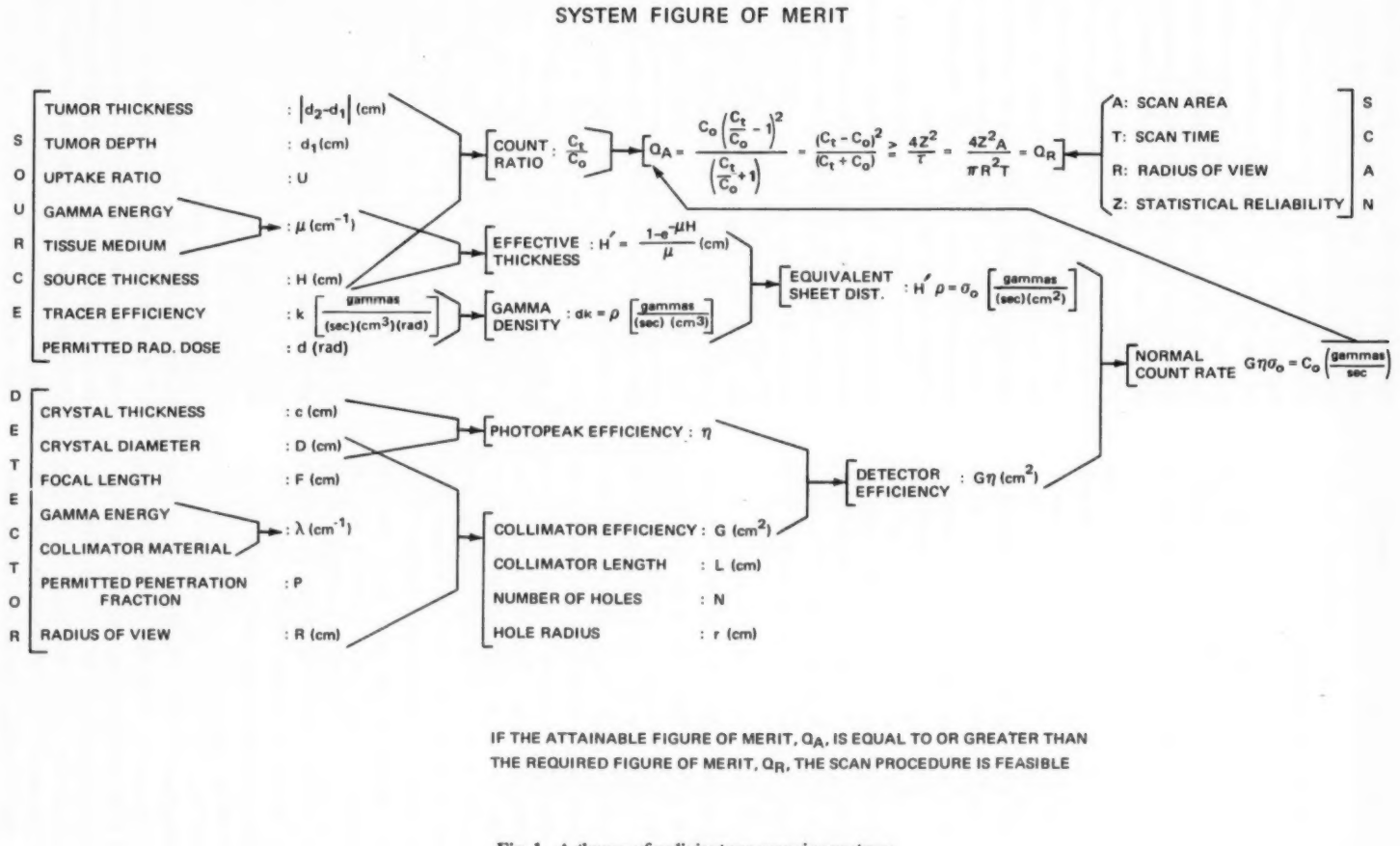

SYSTEM FIGURE OF MERIT
SOURCE
TUMOR THICKNESS : $|d_2-d_1|$ (cm)
TUMOR DEPTH : d_1 (cm)
UPTAKE RATIO : U
GAMMA ENERGY
TISSUE MEDIUM
: μ (cm^{-1})
SOURCE THICKNESS : H (cm)
TRACER EFFICIENCY : k [gammas / (sec)(cm^3)(rad)]
PERMITTED RAD. DOSE : d (rad)
DETECTOR
CRYSTAL THICKNESS : c (cm)
CRYSTAL DIAMETER : D (cm)
FOCAL LENGTH : F (cm)
GAMMA ENERGY
COLLIMATOR MATERIAL
: λ (cm^{-1})
PERMITTED PENETRATION FRACTION : P
RADIUS OF VIEW : R (cm)
COUNT RATIO : $\frac{C_t}{C_o}$
EFFECTIVE THICKNESS : $H' = \frac{1-e^{-\mu H}}{\mu}$ (cm)
GAMMA DENSITY : $dk = \rho$ [gammas / (sec) (cm^3)]
PHOTOPEAK EFFICIENCY : η
COLLIMATOR EFFICIENCY : G (cm^2)
COLLIMATOR LENGTH : L (cm)
NUMBER OF HOLES : N
HOLE RADIUS : r (cm)
$Q_A = \frac{C_o\left(\frac{C_t}{C_o}-1\right)^2}{\left(\frac{C_t}{C_o}+1\right)} = \frac{(C_t-C_o)^2}{(C_t+C_o)} \geq \frac{4Z^2}{T} = \frac{4Z^2A}{\pi R^2 T} = Q_R$
A: SCAN AREA
T: SCAN TIME
R: RADIUS OF VIEW
Z: STATISTICAL RELIABILITY
SCAN
EQUIVALENT SHEET DIST. : $H'\rho = \sigma_o$ [gammas / (sec)(cm^2)]
DETECTOR EFFICIENCY : $G\eta$ (cm^2)
NORMAL COUNT RATE $G\eta\sigma_o = C_o$ (gammas / sec)
IF THE ATTAINABLE FIGURE OF MERIT, Q_A, IS EQUAL TO OR GREATER THAN THE REQUIRED FIGURE OF MERIT, Q_R, THE SCAN PROCEDURE IS FEASIBLE

Fig. 1 A theory of radioisotope scanning systems.

are expressed in similar terms so that Q is expressible in terms of MTF:

$$Q = (C_t + C_0)(\text{MTF})^2 m_0^2$$

Since $C_t + C_0$ is twice the average count rate and therefore proportional to collimator sensitivity, and MTF is a measure of resolution, Q thus effects a compromise between sensitivity and resolution. In the test pattern $m_0 = 1$.

Other measures of resolution are useful in certain applications. The radius, R, of the geometrical field of view at the focus is very helpful as a design parameter, and detailed studies have shown that it is very nearly the optimal size for detecting a space frequency of $1/2R$. The full width at half height of the point-source response function may also be used and approaches very nearly the minimum separation at which two point sources may be disinguished. Both of these approaches have the limitation of attempting to describe the resolution with a single number when it is in fact much more completely described by MTF over the full range of frequency response at any distance from the collimator face.

Data Presentation. The information content of a scan, expressed in the technical language of information theory, has been investigated by several workers. It is possible, by dividing the scan into a number of cells (resolution areas) and summing the information content per cell over the whole scan, to show that an optimal resolution area exists which gives a maximum information content to the scan. The actual value obtained depends on the assumed boundary conditions and the rate at which the count per cell varies with the resolution, and at the moment no clear conclusion is apparent from these studies concerning optimal, practical resolution. Studies in this area merge into the question of what is the best picture for visual interpretation. The question is whether, in scanning, we are trying to detect the presence of something or to depict it in as much detail as possible. Which is the more profitable approach is not entirely clear at present, and the clinician usually appears to be striving to obtain what appears to him to be the best-looking picture.

Most investigators prefer a more direct approach to this question. Operations to remove artifacts from the visual record while it is being recorded or preferably, after it has been recorded, and to enhance statistically valid differences so that a more intelligible picture may be produced have been subjected to much study. Basic artifacts are line structures, statistical structure, and collimator distortion, and, if on-line processing is attempted, time-delay artifacts (scalloping) must also be considered. Although it is possible to perceive an image against a noisy background, it would appear fundamentally desirable to remove the noise if this can be done without losing significant detail of the picture. Line structure can be reduced or removed in two ways: (1) by scanning very rapidly with the lines very close together. This is only possible if no rate-meter circuitry (for contrast enhancement, etc.) is being used. (2) by recording with diffused dots so that adjacent lines overlap. The use of diffused dots also smooths out the statistical variation to any desired degree, depending on the count rate and the dot size. It would appear desirable to be able to vary the dot size with the count rate so that regions of high and low activity would be smoothed equally, and loss of resolution would be reduced in the high-activity areas.

Further information processing can be done in a great variety of ways. Contrast enhancement by rescanning—conversion of different degrees of photographic density to color or to contours—has been done in a number of ways. Parallel readouts with different colors have been used to avoid the scalloping that plagues all other color readouts performed on line. These parallel readouts are then superimposed for the final display. Rescanning mechanically may be done with different degrees of enhancement and background cut off with readout on Polaroid color film to produce superb pictures. Television processing has long been used, more recently with control of the counts in the region of interest so that statistical evaluation is continually available. Color television converts gray shades to easily distinguishable colors. Flying spot scanning provides definitely crisper pictures than the vidicon display because faster circuitry is possible, and the techniques of contrast enhancement and edge enhancement by differentiation and variable smoothing are currently being explored using this approach. The removal of noise from the primary scan by recording with diffused dots carries an additional dividend because adjacent dots overlap considerably and enhance each other so that a form of contrast enhancement occurs by space integration rather than by time integration, thus making such primary records quite usable without further processing.

An entirely different approach to image analysis and manipulation has been available for many years in the optical field, and encouraging preliminary results are being reported with optical filtering of scan images.[10] When a transparent object is illuminated with monochromatic parallel coherent light and then

imaged by a lens, a Fraunhofer diffraction pattern is formed at the principal focus of the lens quite independently of the other image. In this pattern, high space frequencies in the object produce patterns considerably removed from the axis of the optical system, while low-frequency components are imaged in this plane close to the axis. High- (edges) or low- (background) frequency components can thus be enhanced or suppressed by insertion of suitable filters into the interference pattern. Theoretically it thus becomes possible to compensate, within the limitations of statistical noise, for the collimator response, which is greater for low-frequency objects (MTF $\cong$ 1) and becomes less for high-frequency objects as the MTF approaches zero. Partial filtering out of the low frequencies would thus alter the overall MTF to a uniform though lower level; hence the noise limitation of the process. Line structure may be filtered out of an image by this technique, without appreciably disturbing the remainder of the image, by using as a filter the Fraunhofer diffraction pattern of a line pattern of the same frequency as the scan lines in the original image.

This whole area of analog methods of processing has the advantages of flexibility and, in general, inexpensive hardware; and, in the opinion of many, the information in the scan is rarely of a degree of precision justifying routine digital processing.

Numerous other investigators, however, are actively pursuing digital methods. These allow presentation of contours of even steps of activity, or, perhaps more appropriately, even steps of statistical significance. It is in this type of application that digital methods probably have the most importance and, in the opinion of some, should form the firm foundation on which to build analog methods. Special applications, such as operator-monitored variable smoothing, have led to results considerably superior to comparable analog methods. The immediate presentation of scan data as a numerical display with the possibility of summing the total observed counts in various regions of interest may be done with different, rather sophisticated systems of varying degrees of convenience and flexibility. Operations comparable to the optical filtration process have been proposed, e.g., moving each recorded dot up a gradient in the appropriate direction before smoothing and display. Actually, fairly routine operations, such as removal of scalloping by autocorrelation between lines and derivative analysis to enhance edges, may be carried out for only a few dollars per scan after setting up the appropriate program and data-collection systems.

Interest in the use of different scanning modes appears to be growing. The rectilinear projection that is almost universally used superimposes all structures so that frequently it is necessary to obtain scans from different directions in order to localize structures adequately. This approach has been extended to produce three-dimensional mapping in various ways. Longitudinal and transverse section scanning and full three-dimensional displays appear feasible, using the photon flux available with emitters such as ^{99m}Tc and the sensitivity of the Anger camera. Initial results show clearly that useful gains are possible in this direction. Other special applications with cameras exist in addition to the one already mentioned in the discussion of the collimator field of view. The camera can be used like a panorama camera in a scanning mode, with the readout film moving in the readout camera in a linear manner linked to the detector head. This allows the field being scanned to be extended indefinitely, making possible total-body scans with greatly improved sensitivity and resolution over other available configurations. The Anger camera with an opposing scintillation camera head for use with positron emitters produces an analog display of any desired plane and, with appropriate equipment, of all planes simultaneously in the region of interest. This approach has been extended using two conventional camera heads facing each other, quite close together. The readout in each camera head determines the end points of the path of each annihilation pair. Each count is then stored in all possible cells of origin in a three-dimensional grid in a computer memory which simulates the object being scanned. Regions where many pairs originate thus build up counts resulting finally in a full three-dimensional record. This may then be displayed or analyzed as desired. Fixed correction may be introduced for the built-in geometrical distortion. This configuration approaches the ideal of 4π detector geometry as closely as any yet devised and should be particularly useful with short-lived positron emitters. The positron emitters have the additional advantage of being relatively free from attenuation differences since each of the annihilation pairs must traverse an equal total path length in tissue. Quantitative measurements under these conditions become simpler. Count-rate limitation due to pulse pile up appears to be the only serious limitation to this approach.

Other methods of detecting radiation are being explored. The image-intensifier approach is limited by the low front-end efficiency of the input phosphor, although improvement by use of a thicker phosphor looks promising. The unique advantage of the image-

intensifier system is its almost complete freedom from count-rate limitations. The use of pulse-height analysis in the usual sense with an image intensifier does not appear simple, although there have been efforts in this direction. At the present time, the use of image intensifiers with gamma energies of over 150 kev does not appear promising. An interesting development is the spark chamber, which preserves the location of information of a gamma interaction very well. It suffers at present from the same energy limitations as the image intensifier and is sharply count-rate limited. This latter limitation has been circumvented by using a similar device operated in a mode analogous to a proportional counter recording the ultraviolet light emitted in the interactions. The place of these new detectors in the general picture of nuclear medicine is not yet entirely clear, although there is considerable optimism concerning the two-stage image intensifier with television readout.

It is clear from the preceding discussion that the daily clinical practice of nuclear medicine is hard pressed to include all of the current developments in nuclear instrumentation and nuclear chemistry. As a result, a flexible approach to the performance of routine studies is mandatory.

Some generalizations about imaging techniques can be made. In our laboratory it has become routine practice in most cases to obtain several views of any organ examined, since we have more time available with the use of high count rates. This not only increases the diagnostic accuracy and scope of the study but also permits a better exploitation of the medium and lower energy isotopes, since attenuation of the gamma rays in the overlying tissue is significant with these emitters, and consequently both sides of an organ should be imaged separately. We use a very narrow index for all our rectilinear scanning procedures to reduce line structure in the scan and use a relatively high scanning speed. As a result, the total time spent in an area corresponds with a more conventional approach utilizing a wide-stepping function but has the advantage of reducing distortion due to patient movement. In scanning the thyroid, for instance, it is better to make several passes through a region, since, if the patient swallows and thus moves the thyroid gland, the distortion is manifest in only one scan pass and is corrected by the remaining scan passes through the area. If a wide index is used, so that the area is imaged only once, swallowing will distort the entire display in this area. It is clear that a certain amount of data blending in the accumulation of the original data is desirable. This is done by use of a bell-shaped spot in the readout, and, although it is recognized that the optimum size of spot is yet to be determined for each situation, we have empirically selected our spot size to be approximately the same as the FWHM (full-width–half maximum) of the collimator point-source response at the focus.

Organs Studied

Thyroid. Thyroid studies are done with ^{125}I and specially constructed low-energy probes attached to a conventional 3-in. scanner. This has the advantage over the scintillation-camera pictures of providing a life-size display—occasionally important in comparing the scan with the palpated neck—and also of utilizing the low-energy gamma of ^{125}I. Should additional studies be required following TSH (thyroid stimulating hormone) stimulation, or thyroxin suppression, the scan can be repeated with either ^{99m}Tc (as pertechnetate) or ^{131}I. In young people and children, when the question of hyperthyroidism exists, we use pertechnetate as the scanning agent to reduce the radiation dosage.

Liver and Spleen. Liver and spleen scanning are done almost exclusively with the scintillation camera and technetium sulfur colloid. This combination permits such rapid pictures that they can be completed with breath holding, thus obviating the respiratory-motion artifact. In addition, it is a simple matter to obtain multiple views—important in the careful examination of such large organs. Occasionally, if a subphrenic or hepatic abscess is suspected, it is necessary to obtain a life-size display for comparison with roentgenograms to discover the relationship of the right diaphragm to the functioning hepatic parenchyma. In this connection, transmission scans provide the ideal answer. In these situations, a frontal scan (done at high speed with relatively poor overall resolution) is also included. Spleen visualization by transmission and frontal scans is perfectly adequate for all purposes except perhaps for blood-flow studies, so that we do not feel a great need for BMHP (bromomercurihydroxypropane) or chromated red-cell studies.

Brain. Brain scanning is done on the Argonne Cancer Research Hospital brain scanner. This was originally built as a flexible multipurpose machine, but the detectors have recently been redesigned and optimized for ^{99m}Tc. The machine is designed to give high resolution with great depth of field. To accomplish this, the collimators utilize only the central 2.5-in. portion of the 3.5-in.-diameter crystals. This results in

a decreased sensitivity, which is partially compensated for by using two pairs of opposing detectors. The machine is constructed to do two simultaneous views. In a routine scan using .0 mc of pertechnetate, each detector sees count rates up to 20,000/min, so that frontal and posterior views and both lateral views are obtained in about 10 min for each pair. A complete study includes all four projections of the head and takes 20 min of scanning time. The resolution obtained is superior to that of the Anger camera, which is reserved for squalling, squirming infants where examinations lasting only a few seconds are necessary.

Others. Certain studies are done on a combination of instruments. For example, lung scans and placental scans are done on both the 3-in. rectilinear scanner and the Anger camera. For the lung scan the routine frontal and posterior views are done on the conventional scanner, since in general the desired field of view is larger than that obtainable with the gamma camera with the usual parallel-hole collimator. Lateral projections, however, are nicely obtained with the camera and are a valuable adjunct to the examination. Similarly, a placenta scan is started with a large frontal view and done at high speed with the conventional scanner, but this is followed by appropriate lateral and oblique views with the camera to further aid in localizing the placenta once the large scan has been obtained. Kidneys are easily localized for biopsy by first transferring the renal outline from a dot scan to the skin on the patient's back and then confirming the correlation to the underlying kidneys by placing external isotope marker sources on the outline and using the scintillation camera to prove that this represents the underlying kidney. Parathyroid scanning has been immensely improved by administration of selenomethionine into the thyrocervical trunk under fluoroscopic control.

Conclusions

We think that it is gradually becoming obvious that the time has come for diversification in nuclear instrumentation and that the best answer to the question, "Which scanner do I buy?" is, "At least one of each type, with all the attachments." When the choice lies between two commercial scanners of the same general type, the problem is much more difficult. The differences in objective performance become rather trivial, and practical considerations such as serviceability are of greater importance. Again, we have attempted to convey a feeling for the state of the art of scanning, and we wish to acknowledge freely our debt to our many colleagues in the field of nuclear medicine whose thoughts and conversations have contributed much to this presentation. (JEC and PSB)

Note by J. H. Lawrence, M. D. and editor of the book from which this chapter is reprinted:

The above is an excellent discussion of important factors in various scanning situations and the advantage of a particular approach for solving a specific problem. Related to this chapter is the widespread use of scanning procedures in practice today. With the availability of scanners and cameras permitting visualization of the distribution of radioactive substances within the living body, the physician is able to assess in some degree the size, shape, position, and function of organs, and also, sometimes, to locate lesions therein. In looking over the program for the recent meeting of the Society of Nuclear Medicine and noting the large number of papers concerned with scanning as well as the many commercial exhibits demonstrating isotope scanners and cameras, one realizes that there is much activity in this area. Important progress has been made; scanners and cameras are being used to study almost every organ of the body: thyroid, brain, liver, kidney, lung, spleen, bone marrow, pancreas, parathyroid, stomach, colon, placenta, heart, myocardium, and bone, and efforts are being made to find satisfactory methods for visualizing the prostate, adrenal, peripheral and cerebral circulation, eye, cerebrospinal fluid and choroid plexuses of the brain, salivary glands, lymph nodes, and joints. In addition, dynamic scanning is receiving attention as recent computer and technical developments have permitted rapid quantitative observations of the blood passing through a variety of organs as a bolus; because of the quantitative nature of the information obtained, this approach of simultaneous counting and visualization using short-lived isotopes may become competitive with roentgen angiography in some situations. The use of ultrashort-lived (few-second) emitters is of particular interest in this application, because this would eliminate the effects of recirculation.

Although these methods are still relatively crude, as are diagnostic X rays in many instances, nevertheless, scanning has had a great impact on medical practice and research, and, with the possibility of producing and using new labeled compounds aided by computers, further progress can be expected. However, even though we have the ability to scan most organs of the body, we are still limited in being able to detect neoplasms in these organs during the early stage of their growth. At present, hope for the ability to treat successfully more patients with cancer would seem to lie in earlier diagnosis, and scanning could become very important in providing a method for achieving this. There is really no "early" detection for most cancers at the present time; by the time the tumor is detected it is often already too late. Yet, we know that, with a size-doubling time of 100 days, it would require 5 years for some tumors to increase in size from a cubic millimeter to a volume large enough to cause symptoms or signs in some areas of the body. We also know that with scanning and X-ray diagnosis, in many instances the tumor or cancer has to have perhaps 10^9 cells within its substance before it can be detected. Scanning in combination with still-to-be-discovered radioactive compounds which might selectively localize in cancer tissue could provide a method for detecting smaller

neoplasms (perhaps 10^6 cells). Then it might be possible to remove the tumor during this early period of growth before it has metastasized, and thus lead to the curability of many more patients with cancer. Fluorine-labeled 5-fluorouracil has possibilities here.

References

1. R. M. Kniseley, G. A. Andrews, and C. C. Harris (Eds.), *Progress in Medical Radioisotope Scanning,* Oak Ridge, Tenn., Oct. 22–26, 1962, AEC Symposium Series, No. 1 (TID-7673), 1962.
2. *Medical Radioisotope Scanning,* Symposium Proceedings, Athens, 1964, Vols. I and II, International Atomic Energy Agency, Vienna, 1964 (STI/PUB/82).
3. *Scintillation Scanning in Clinical Medicine,* based on a symposium, Winston-Salem, N. C., Jan. 30–31, 1964, J. L. Quinn, III (Ed.), W. B. Saunders Company, Philadelphia, 1964 (CONF-640101).
4. *Fundamental Problems in Scanning,* Proceedings of a symposium sponsored by Argonne Cancer Research Hospital, Northwestern University School of Medicine, and Abbott Laboratories, Chicago, Ill., May 8–9, 1965, A. Gottschalk and R. N. Beck (Eds.), to be published by Charles C Thomas, Springfield, Ill.
5. G. A. Andrews, R. M. Kniseley, and H. N. Wagner (Eds.), *Radioactive Pharmaceuticals,* Oak Ridge, Tenn., Nov. 1–4, 1965, AEC Symposium Series No. 6 (CONF-651111), April 1966.
6. J. R. Mallard, Medical Radioisotope Visualization (A Review of "Scanning"), *Int. J. Appl. Radiat. Isotop.,* 17(4): 205-249 (1966).
7. R. N. Beck, Radioisotope Scanning Systems, *ISA (Instrum. Soc. Amer.) Trans.,* 5: 335-348 (1966).
8. H. O. Anger, Survey of Radioisotope Cameras, *ISA (Instrum. Soc. Amer.) Trans.,* 5: 311-334 (1966).
9. J. G. McAfee and G. Subramanian, Radioactive Agents for the Delineation of Body Organs by External Imaging Devices: A Review, *ISA (Instrum. Soc. Amer.) Trans.,* 5: 349-372 (1966).
10. E. L. O'Neill, Spatial Filtering in Optics, *IRE [Inst. Radio Eng. (now Inst. Radio Elec. Eng.)] Trans., Info. Theory,* IT-2: 56-65 (June 1956).

Other articles on the subject of scanning that have been published in *Isotopes and Radiation Technology:*

M. Brucer, Sixty-Five Years of Medical Radioisotope Scanning, *Isotop. Radiat. Technol.,* 6(1): 109-113 (Fall 1968).

J. E. Carden, The Anger Camera, *Isotop. Radiat. Technol.,* 5(1): 45-53 (Fall 1967).

The Application of Neutron Activation Analysis to Cystic Fibrosis Detection*

By Philip Howard Heintz

Cystic fibrosis (CF), a children's disease that affects digestion, breathing, and perspiration, was first described in 1938. To date, no cure is known, but it has been found that early diagnosis and treatment will permit a reasonably normal life. A rapid, simple means of diagnosis would detect those cases presently undiagnosed (estimated to be 50%) and thereby lower the age of diagnosis. Neutron activation analysis (NAA) offers a fast, inexpensive, mass-sample technique adaptable to this purpose.

Cystic fibrosis is a hereditary disease incident chiefly in the Caucasian race (about 5% are carriers of the disease). Detection has been by measurement of the abnormally high sodium and chlorine contents of body sweat; however, this test is unsuitable for mass screening because it is time-consuming and expensive. As alternatives, analysis of hair and of nail clippings has been suggested. Neutron activation analysis has been previously used for hair analysis; the well-known principles and techniques are equally applicable to nail clippings.

Unfortunately there are many technical problems involved in NAA of hair. Containers, static electricity, and geometrical considerations cause irreproducibility. Various shampoos and hair treatments contaminate hair to the extent that results are difficult to reproduce or to interpret intelligibly; hence NAA of hair is useless as a diagnostic tool.

Since nail clippings are easily obtained and have been shown to be a reliable indicator of characteristic trace elements in the body, the analysis of sodium in

*This is an abstract of a thesis submitted in partial fulfillment of the Master of Science Degree in Engineering, University of Washington, Seattle.

nail clippings was studied. A standard procedure was devised for collecting, cleaning, and handling the clippings, and a FORTRAN program was used to compute the electrolyte concentrations as well as the standard deviation of the group of samples.

As a sidelight, when checks were made of those CF patients with low-sodium samples, these patients were shown to be in congestive heart failure at the time of sampling. Studies showed that almost every patient's nail sodium dropped just prior to heart failure and returned to normal after recovery. In contrast, conventional sweat tests showed a slight increase in blood sodium.

Nail clippings from relatives and siblings of CF patients were analyzed in hope of finding a method for detecting carriers of the disease. Siblings of CF children showed a slight increase in nail sodium over that of normal children. The ability of NAA to analyze extremely small samples opened the way to the study of baby and infant nails. The development of correct sampling conditions was the most important factor in the attainment of reproducible results. Although insufficient data have been obtained to establish norms, with more work, diagnostic criteria should be forthcoming, which will enable CF detection in infants.

Because contamination is such a serious problem in NAA of hair, methods of washing and cleaning nail clippings were studied. Hydrochloric acid and alcohol were tried as washes. Upon repeated washing, water-based solvents removed over 90% of the sodium, but alcohol removed only about 15%. Abrasive-type cleaners were also tried but proved unsuccessful.

Cleaning tests showed clearly the presence of two sodium components—one on the surface and the other contained within the nail. The same result has been shown in a study of animal hair. Other interesting observations were made from special tests. Aging has no significant effect on sodium content of nails. The recovery time for sodium content after washing is a matter of a few hours. Finger-guard tests indicate that the sodium content of the nail comes from near the nail itself, possibly from sweat glands around and beneath the nail. Sodium content of the plastic vial containers may be as high as 50% of the total sodium content of a typical nail sample. Hence containers are usually changed after irradiation and prior to analysis. Other elements could not be detected in the presence of the sodium and chlorine spectrum which obscures the activity of elements present in comparatively low amounts. (FJM and PSB)

Radiochemical Methods of Enzyme Assay*

Radiochemical methods of enzyme assay, which are very sensitive and accurate, are in common use, but the details of the methods are often buried in technical papers. Since neither the title nor the abstract of these papers leads the reader to the method, K. G. Oldham of the British Radiochemical Centre at Amersham has compiled radiochemical assay methods from 180 published articles. These represent only a small part of the published literature, but three review articles included in the bibliography provide the reader with additional sources of information.

The review describes various methods for assaying a number of enzymes, together with modifications that have been introduced for the basic methods, and includes a critical examination of current and potential uses of radiochemical methods of enzyme assay. The booklet is organized into three sections. Section A discusses the techniques that have been used in radiochemical assays of enzymes, with special reference to possible sources of error in both the assay and the interpretation of results. Section B considers examples from each class of enzyme, describes the types of radiochemical assay that have been used in studying these enzymes, and comments on the advantages and disadvantages of the assays. Section C reviews factors important in radiochemical assays of enzymatic activity.

The chief objection to enzyme assays in the past has been to the time required, but the techniques used in radiochemical methods have overcome this objection. Rapid and simple sampling and separation procedures, which can easily be performed by technical assistants, are now available for most enzyme assays. The techniques are very versatile, offer extremely high sensitivity and specificity, and give accurate and reproducible results. They offer many advantages over

*Summary of booklet by K. G. Oldham, *Radiochemical Methods of Enzyme Assay*, Review 9, The Radiochemical Centre, Amersham, England, 1968 (48 pp.).

conventional methods for nearly all assays other than those carried out during the study of the kinetics of reaction of highly purified enzymes, where continuous assays may be essential. If a suitable labeled substrate is chosen, most reactions can be followed in either direction, and most of the troubles caused by interfering reactions can be avoided. This specificity, and its resulting freedom from interference, makes radiochemical assays very suitable for use on crude extracts and for studying the effects of activators, inhibitors, and *p*H variation. Since the sensitivity of these assays enables them to be used over a wider range of substrate concentrations than is possible by other methods, they are very suitable both for the determination of Michaelis constants and for the study of competitive inhibition at very low substrate concentrations. This sensitivity also permits enzyme assays to be carried out with crude tissue extracts at very high dilution, thus decreasing the effect of any competitive inhibitors that might be present; moreover, it facilitates the assay of low levels of enzyme activity and of the enzymatic activity of microgram quantities of tissue such as might be obtained in needle biopsies or during a survey of enzyme distribution throughout an organ. Radiochemical assays have proved very useful in determining the in vivo activity of enzymes that have been inhibited by drugs, for example. Conventional assays, in which the enzyme is appreciably diluted and high substrate concentrations are used, cause the in vivo inhibition to disappear and false high rates of enzyme action to be observed.

In summarizing the advantages of radiochemical methods of enzyme assay, the author of the review predicts that these methods will prove to be an increasingly useful tool in both general and clinical biochemistry, particularly in the study and diagnosis of diseases caused by inborn errors of metabolism due to inherited enzyme defects. They can also be expected to make a significant contribution to our knowledge of the effects of drugs on enzymatic activity. (MG)

Isotopes and Radiation in Parasitology

Abstract: *The proceedings of a research coordination meeting on isotopes and radiation in parasitology held in Vienna, July 31 to August 4, 1967, are summarized. All 16 papers are presented in condensed form. Most papers reported results of immunization experiments using irradiated larvae of parasites. Tracer studies of the effects of parasites on hosts are also included. The recommendations of the meeting are given.*

The use of ionizing radiation to produce vaccines against helminthic diseases and the use of radioisotopic tracers to study the immunology and pathophysiology of helminthic and other parasitic diseases have been considered by the International Atomic Energy Agency[1,2] in previous years. In 1966, a coordinated research effort entitled "The Use of Isotopes and Radiation in Studies on the Etiology, Effects, and Control of Parasitic Diseases in Domestic Animals" was initiated. Although originally limited to parasites in domestic animals, the program obviously could not be kept within artificial species barriers, especially in view of the similarity of certain parasitic infections in man and animals and the existence of cross infections. The main aim of the program was restated as the contribution to the control and subsequent eradication of major parasites of farm animals, acknowledging that work on other species of direct relevance to the problem was necessary. Laboratories in Czechoslovakia, Denmark, Hungary, Israel, Italy, Kenya, Yugoslavia, the United States, and the United Kingdom are coordinating their efforts in this program. The chief investigators met in Vienna, July 31 to August 4, 1967, to report on and discuss their findings. Some experts in parasitology not taking part in the program also attended.

Summaries of Research

Varga[3] (Hungary) reported that experimental immunization of poultry against gapeworm disease by means of a radiation vaccine* provides a high degree of protection to the vaccinated bird. The gapeworm is a roundworm (*Syngamus trachea*) that adheres to the tracheal mucosa and causes death by suffocation when present in sufficient numbers. It is especially prevalent in developing countries. Domestic chickens become resistant as they grow older, but turkeys, pheasants, and partridges are susceptible even as adults.

*"Radiation vaccine" throughout these summaries refers to an injection of radiation-weakened larvae.

Eggs and larvae of *Syngamus trachea* were irradiated with an X-ray machine (190 kv, 15 ma) or ^{60}Co. Radiation effects were assessed by counting the number of larvae developing after 14 days of incubation. Retardation was directly related to dose, with gamma rays requiring 20% higher dose to produce the same effect as X rays. An 8-kr dose from ^{60}Co reduced the number of developing larvae to less than 30%; 8 kr from the X-ray machine prevented more than 90% of the larvae from developing. One-day-old chicks were infected with 400 irradiated larvae and slaughtered between the 9th and 41st days of life to judge the degree of infection. At doses of 4 and 8 kr, few or no worms were found in the trachea.

New Hampshire chickens were administered 800 irradiated larvae (5 kr) at 2 weeks of age and 1200 irradiated larvae 1 week later. After a further 2 weeks, each chicken was challenged with 1500 normal larvae. All birds were killed at the age of 7 weeks; birds receiving irradiated larvae had only 2% as many gapeworms as did the controls that received the same challenge.

Chicks receiving 800 irradiated larvae at ages of 1 day and 4 days were challenged at the age of 2 weeks with normal larvae and slaughtered 2 weeks later. Birds receiving the irradiated larvae had only 6% as many gapeworms as did the controls. The immunizing dose was later reduced to 500 irradiated larvae to prevent the development of lung lesions. One group of chickens immunized when 1 day old was challenged at 2 weeks with 2000 normal larvae per bird. Four weeks later, all chickens in the test group were living, but 8 of the 12 controls had died of syngamosis.

The dose is important. Larvae irradiated at 5, 10, and 20 kr were applied in identical tests. These doses gave 93, 51, and 0% protection, respectively. Obviously, if the immunizing larvae are given too large a dose, they die and therefore provide no protection.

Field trials in three categories have been carried out: poultry groups immunized in the laboratory and placed on infected ground, poultry groups immunized at the owner's and grown with owner's control group on infected ground, and poultry groups immunized and grown in infected areas where comparison was made between pre- and postimmunization mortality. In the first category, protection was 93 and 88% in the two groups tested. In the second category, protection varied from 53 to 91%. In the third category, of five groups tested, the highest mortality was 11%, as contrasted to a history of 80% yearly losses.

The experiments show that vaccination can work on turkeys, chickens, and pheasants. Vaccination with radiation-attenuated *Syngamus* larvae should take place with 1-day-old chicks; further treatment is judged to be uneconomic. Ideally, to establish full immunity with chickens, they should be vaccinated soon after hatching, prior to the first feeding, and raised in isolation for 2 weeks. Further studies on practicality are needed.

Miller[4] (Scotland) reported that an X-irradiated vaccine for ancylostomiasis (infection with the dog hookworm, *Ancylostoma caninum*) will be in commercial use in the near future to protect dogs against the hookworm disease. The vaccination is best used in two doses given 1 month apart to dogs 3 to 4 months old.[5,6] Application by subcutaneous inoculation is better than oral administration.[7] Immunity persists for at least 8 months.[8] Vaccination of the young bitch reduces prenatal infection in her pups by 80 to 90% as compared to pups born to unvaccinated bitches.

Fitzpatrick and Mulligan[9] (Scotland) reported a marked decrease in radiosensitivity of *Nippostrongylus brasiliensis* larvae with increasing temperature. This is probably due to a more rapid reduction of the oxygen content of the suspension at higher temperatures as a result of greater metabolic activity of the larvae. This temperature effect is lowest at 15 to 20°C. Further investigations are under way to determine whether or not there is an independent effect of either temperature or oxygen on irradiation of this helminth.

Prochazka and Tomanek[10] (Czechoslovakia) studied the effects of temperature of storage, length of storage, X-ray dose rate, and filtration on infective larvae of the bovine lungworm (*Dictyocaulus viviparus*). The initial viability of larvae used was 97.3%. After 5 weeks' storage at 4°C, the larvae were 82% viable. However, after 5 weeks at room temperature (about 20°C), the larvae were only 40% viable. Refrigerated larvae were significantly less invasive after 4 weeks, but the larvae stored at room temperature became significantly less invasive between 2 and 4 weeks. Mortality of refrigerated larvae was 17% at the end of 5 weeks and of those held at room temperature, 30%. This temperature effect probably results from the fact that *Dictyocaulus viviparus* larvae take in no food during their ectogenous development, and high storage temperatures would make them consume their food reserves more rapidly.

As a test of the effectiveness of the irradiated larvae over a period of storage, the time after irradiation at which the host-invading ability of the larvae is reduced was determined and compared to that of normal larvae. In general, no differences were noted over the period of storage. However, larvae tested shortly after irradiation showed a marked decrease in

invasiveness; at 24 hr after irradiation, no such decrease was evident.

Apparently, the most important fact in X-irradiation of parasites is the total dose of radiation. Infective larvae of *Dictyocaulus viviparus* were irradiated with X rays to a total dose of 40 kr at 250 and 500 r/min. Parameters used were 180 kv, 15 ma, and 0.5 mm Cu + 0.5 mm Al filtration. In another run, total exposures were from 10 to 50 kr, dose rates were 280 and 795 r/min, and filtration was 0.5 mm Cu + 0.5 mm Al or 2.5 mm Al. No significant differences with dose rate or with different filtration were noted. This agrees with other reports.[11,12]

Urquhart[13] (Scotland) reviewed the immune response of young animals to infection with X-irradiated and normal nematode larvae, concentrating on the difficulty of producing a degree of useful immunity before infection by the pathogen and on the possibility that young animals may be incapable of developing a good immune response. With the commercially available irradiated vaccine for use against the bovine lungworm *Dictyocaulus viviparus,* these problems do not arise because most dairy calves in Europe are born indoors and do not go to grass until they are 4 to 6 months old, when vaccination is complete and immunity is established. Similarly, beef calves raised on grass have shown good response to vaccine. However, attempts to develop a vaccine against *Haemonchus contortus* for lambs have shown that Blackface sheep can be protected by a double vaccination after they are 6 months old, but that 2- to 3-month-old lambs are unresponsive.[14] Attempts to vaccinate adult East African Merino sheep raised in an endemic area were unsuccessful, and treatment to reduce infection before vaccination and challenge was also unsuccessful in establishing immunity. In another experiment with three age groups of Merino sheep, only a group vaccinated at 2 years of age was successfully immunized against *Haemonchus contortus.*

The limited information available supports the conclusion that very young animals cannot be as successfully immunized as older ones. The possibility of immune unresponsiveness is being studied by infecting young rats with *Nippostrongylus brasiliensis.* Four phases of infection in adult rats have been observed: (1) loss phase 1, during which larvae die before they reach the lungs; (2) plateau phase, during which the parasite population is static; (3) loss phase 2, during which there is an exponential loss of worms from the intestine; and (4) threshold phase, during which a residual burden remains in the intestine after the 18th day.

In young rats, loss phase 2 does not occur, and they retain a large infection into their adulthood. Baby rats might be inefficient at antibody production, but this would not explain the persistence of the plateau phase in the adult rat. There are three possible explanations: (1) The primary immune response in young rats may be restricted; the young rats produce reaginic antibody to *Nippostrongylus brasiliensis* antigen, but the antibody is demonstrably not protective. (2) Antigen production by the adult worms may cease or diminish while the rats are still young so that there is no stimulus of critical antibody. (3) The existence of an established worm infection during the immunologically immature period of the rats' development may exhaust a particular cellular response necessary for combating the infection.

Sadun et al.[15] (United States) reported the results of a study of the relative role of eggs and adult worms in causing liver damage in mice infected with *Schistosoma mansoni.* This is a subject of great controversy. Numerous publications[16-22] emphasize the importance of dead worms in causing liver damage by obstruction of the intrahepatic portal radicles followed by focal necrosis due to tissue ischemia. Other reports[23-25] indicate that dead worms are of minor importance and that any treatment which kills worms is beneficial rather than damaging to the patient. Advances in ultramicrobiochemical techniques have made possible the quantitative determination of serum components in mice during infection with parasites.[26] Significant deviations in normal liver tests occurred with small infections of worms and appeared to accompany egg deposition. A dose of 3000 rep will prevent cercariae from maturing and producing eggs.[27] A new nonantimonial compound, when given to mice in doses of 100 mg/kg for 10 consecutive days,[28] will also prevent egg formation by *Schistosoma mansoni.*

Studies were undertaken to determine whether or not liver damage from *Schistosoma mansoni* infection is transitory, to assess the relative roles of eggs and adult worms in hepatosplenic schistosomiasis, and to evaluate treatments before and after significant deviations in liver-function tests. Abnormalities were examined in levels of serum glutamine pyruvic transaminase, serum glutamic oxaloacetic transaminase, and total protein.

Mice treated with 1-(5-nitro-2-thiazolyl)-2-imidazolidione after being infected by the schistosome parasite had an average of only 2.2 stunted worms in their livers as opposed to an average of 24.5 worms in the livers of untreated mice. Levels of transaminase rose slightly during the first 5 weeks of infection,

increased significantly at the onset of egg laying, but decreased to preinfection levels after treatment. To test the effect of heavy infestation, worms irradiated to prevent egg formation were used. The source of radiation was a 1300-curie Gammacell 220 ^{60}Co irradiator.* The drug was given to half the animals. At necropsy, an average of 29.5 worms was recovered from untreated animals and an average of 13.1 worms from the treated animals. No consistent significant changes in transaminase values were observed. A third experiment tested the hypothesis that drug treatment might cause biochemical changes in uninfected mice; however, no evidence was found to support this idea.

The results of these experiments leave little doubt that the egg is the main pathogenic agent in schistosomiasis; dead adult schistosomes apparently cause lesions of a focal character in the liver. Evidently, chemotherapy, by suppressing the egg-laying function of schistosomes, can prevent the marked cellular response to eggs that results in the formation of fibrous tissue.

Wellde and Sadun[29] (United States) produced resistance to *Plasmodium berghei,* a mammalian malaria parasite, in rats and mice by injection of irradiated parasites. In previous work, moderate degrees of success have been obtained in attempts to induce immunity in rats and mice with killed parasites and crude antigens. Drug therapy has also been successful. Irradiation of parasites interferes with their physiologic processes and frequently inhibits their normal development and multiplication. The use of irradiated parasites as vaccines could take advantage of the special immunological properties of living parasites while suppressing the pathogenic effects of the vaccine.

Male albino rats were immunized with blood taken from infected rats, which was standardized at 2×10^8 red blood cells per milliliter and irradiated in a 1300-curie Gammacell 220 ^{60}Co irradiator. Immunizations and challenges were given intraperitoneally. All animals injected with parasites exposed to doses up to and including 16 kr became infected; some animals injected with parasites irradiated at 17 and 18 kr became infected; only one animal injected with parasites irradiated at 19 kr and above became infected. In another experiment, animals were injected with parasitized blood irradiated at 20 kr; they were then challenged 1 week later with nonirradiated parasitized blood. A significant difference between the immunized rats and the controls was noticeable 10 days after challenge, and peak parasitemias reached in the immunized group were significantly lower than those of the controls. A further experiment involved five groups of rats: one group received irradiated infected red blood cells; one, irradiated plasma from parasitized blood; one, irradiated noninfected blood; one, irradiated plasma from noninfected blood; and one, an irradiated saline citrate solution. As before, the animals inoculated with irradiated parasitized blood responded with significantly lower parasitemias, but no differences were noted among the other four groups treated—i.e., the controls—after the challenge infection was injected. Another experiment gave results indicating that a number of immunizing doses prior to challenge gives a better degree of protection.

In a series of experiments with the mouse, a more susceptible animal, one group of mice received immunizing doses of irradiated infected red blood cells; a second, irradiated normal mouse blood; and a third, nothing. When challenged by injections of infected blood, the controls and the group receiving normal mouse blood suffered complete mortality. Mortality was delayed in the immunized group, and two mice survived. A second experiment showed that the degree of resistance increased with the number of immunizing doses. Five of 35 mice receiving five doses survived; 6 of 20 mice receiving 10 doses survived. Another experiment tested the length of the induced immunity by challenges given 1 week and 2 weeks after the last immunization. Mean survival times were longer in immunized groups than in controls although only 3 mice survived in the group challenged at 1 week, and no mice survived in the group challenged at 2 weeks.

All these experiments reveal, in general, that resistance to *Plasmodium berghei* is induced in rats and mice by vaccination with the irradiated parasite. The induced resistance considerably lowers the parasitemia levels and permits some mice to survive otherwise lethal infections. The degree of acquired immunity is directly proportional to the number of immunizing doses. The mouse experiments are noteworthy in that this is the first time that a significant number of mice have been able to interrupt an established infection without chemotherapy. Also, even in the mice not completely protected, the onset of parasitemia was significantly slower than in the controls. The minimum effective dose for irradiation of parasitized red blood cells seems to be 19 kr.

Sadun[30] also reported briefly on the immune mechanisms in mice treated with irradiated *Plasmodium berghei.* In mice immunized with five doses of irradiated parasites and challenged 1 week after

*Manufactured by Atomic Energy of Canada Limited.

immunization, gamma globulins increased significantly, and the serum collected contained protective antibodies. Parasitemia persisted in the immunized mice, however. The antiserum was relatively ineffective against parasites from the immunized mice, indicating the presence of a suspected variant strain of parasite. Mean spleen weights of immunized mice were double those of controls.

The immune response of cattle infected with *Trypanosoma brucei* and the antigenic variation of infecting organisms were investigated by Cunningham and Grainge[31] (Uganda). In cattle infected with this parasite, the trypanosomes develop variant antigens, and in response the cattle develop various antibodies.[32] Five trypanosomiasis-free East African shorthorned zebu cattle were infected and sampled periodically. After being cultivated in mice, the parasites were preserved alive at −80°C for use as antigens in serological tests: agglutination, neutralization, agar-gel double diffusion, and indirect fluorescent antibody tests. Antigens caused production of agglutinins beginning the sixth day after infection and reaching a peak during the second or third week; agglutinins were detectable in serum samples collected 250 days after injection. When serum samples were used as antigens, agglutinins were also produced. Neutralizing antibodies were detectable by the sixth day, reached a peak during the second week, and fell gradually but were still detectable the 226th day after injection. Lines of precipitation,* which were detected by the agar-gel double diffusion test by the tenth day after infection, increased in number and intensity until the 150th day. Antibodies were detectable using the indirect fluorescent antibody test during the second week of infection, and they were present until at least the 320th day after infection.

Trypanosoma brucei produces a succession of antigenic variant populations, probably at less than 7-day intervals, each of which is produced only once during the infection. These antigenic variations have antigens in common. If the infection is mild, the homologous agglutinins and neutralizing antibodies produced by the cattle will maintain a delicate balance against the antigenic variants, and the parasite will die out. This theory is supported by reports[33,34] that animals subjected to sudden stress, as in vaccination against another parasite or capture, sometimes die of trypanosome parasitemia.

*Solutions of antigen and antibody are placed on agar gel at separate locations. They diffuse through the agar gel, and reaction lines (if any) appear at the interface.

Cunningham[35] (Uganda) induced resistance to trypanosomes in cattle by infection and chemotherapy. When laboratory rodents are cured of trypanosomiasis by drug treatment, they resist challenge by the same organisms for some time.

Six cattle were infected by intravenous injection, and six cattle were held as controls. The injected animals were all parasitemic 7 days later. All 12 animals were given Berenil (7 mg/kg of body weight) 2 weeks after inoculation. At 1-month intervals after treatment, two cattle from each group were challenged with a light dose of trypanosomes. Of the four cattle challenged at the end of 1 month, one control animal tested parasitic once, but all four cattle tested non-parasitic afterward. Of the four cattle challenged at the end of 2 months, one of the vaccinated group and both controls became parasitemic. Of the four cattle challenged at the end of 3 months, both controls became infected but neither of the vaccinated animals did. The four animals challenged at 1 month were challenged again 8 months later; both controls became infected but neither of the vaccinated animals did. Since all the control cattle challenged more than 2 months after treatment with Berenil became infected and all but one of the animals that were cured of trypanosomiasis by treatment with Berenil resisted further infection, the cured animals apparently acquired an immunity.

The clinical and immunological response in mice to infection with irradiated and normal fluke cysts (*Fasciola hepatica*) was studied by Sokolić[36] (Yugoslavia). From reviews[37-39] of the immunological response to *Fasciola hepatica,* definite conclusions can be stated on immunity to fascioliasis. Information is lacking on the relative importance of irradiated flukes as the source of antigens, on dose and time of administration, on host species' responsiveness to the infection, on pathogenesis and histopathology of subsequent infections, and on the roles of the liver and Kupffer cells in these infections. The effect of serums of infected host species on immature flukes has not been extensively explored.

Sokolić induced some resistance to flukes in mice. Three groups of 120 mice each were infected, each animal receiving 5 normal cysts or 20 cysts irradiated at 3 kr or 100 cysts irradiated at 3 kr. Four weeks later, half of each group was reinfected with the same number of cysts. Weight losses were 28% in the group receiving normal cysts, 23% in the group receiving 20 irradiated cysts, and 30% in the group receiving 100 irradiated cysts as compared to controls. Body weights of the groups receiving irradiated cysts

returned to starting values 6 weeks after infection, but the group receiving normal cysts stayed 22% below their starting weights. The number of red cells decreased from 7.7×10^6 per milliliter in controls to 4.0, 4.1, and 3.7×10^6 per milliliter in mice infected with 5 normal, 20 irradiated, and 100 irradiated cysts, respectively. The number of white cells varied widely; the white cells averaged 9300 per milliliter in controls, but varied from 3400 per milliliter in mice 4 weeks after infection with 5 normal cysts to 19,900 per milliliter in mice 4 weeks after reinfection with 100 irradiated cysts. No hemagglutinating antibodies were found over an 8-week period in serums from mice inoculated with either normal or irradiated cysts. Production of complement-fixing antibodies was stimulated by both normal and irradiated cysts.

Antigens of liver fluke are highly important to immunological study. Each fluke contributes only small amounts of antigens, yet quantities sufficient to stimulate protective immunity might also be lethal. Immunological studies have to wait for sufficient quantities of protective antigens to be developed from in vitro culture of immature flukes. However, irradiated flukes could be used, now that reduced pathogenicity of irradiated flukes has been established.

Casarosa[40] (Italy) experimented with irradiation of animals that had helminthic infections. Many researchers[41] have studied the effects of whole-body irradiation on resistance to viruses and bacteria, and research on the effects of radiation on natural and acquired immunity has shown that innate immunity is suppressed.[42] Research on hosts not previously injected with antigen has given positive as well as subnormal responses. In hosts previously sensitized, the secondary response is normal when antigen is injected before irradiation and subnormal when injected after irradiation.[43] Study on whole-body irradiation in connection with helminthic infections has been limited. Rats preinfected with *Trichina spiralis* and irradiated with 8.8 or 6.4 mc of radium showed retardation of development of the parasite.[44]

A reduction in number and an inhibition of growth of helminthic parasites in irradiated mosquitoes have been demonstrated.[45] Irradiating the host and then injecting the parasite resulted in host mortality or higher infection than usual.[45,46] Mice previously immunized against *Trichina spiralis* were irradiated with 600 rep from ^{60}Co and challenged with 1500 larvae. There were no survivors, but 97.5% of animals irradiated and not challenged or immunized and 74% of animals challenged and immunized but not irradiated did survive.[47]

Guinea pigs were subjected by Casarosa to total-body X radiation; they were then challenged at 4 hours and at 4 days after irradiation. Other groups were irradiated but not challenged and challenged but not irradiated. Ten days after irradiation all the animals challenged at 4 hr and 70% of the animals challenged at 4 days were dead. On the 30th day, the animals irradiated but receiving no further treatment had a 50% mortality, which gave a good check on the experiment because they had been given an $LD_{50/30}$ dose. There were no deaths in the animals that were not irradiated. The early deaths of irradiated and infected animals were evidently due to severe hemorrhages in the lung caused by helminthic trauma, together with blood dyscrasia from total-body X irradiation.

Tracer experiments with ^{131}I and ^{51}Cr to elucidate the pathophysiology of *Fasciola hepatica* infections were described by MacLean et al.[48] (Scotland). Some researchers think that the liver fluke lives mainly on blood and that the anemia and hypoproteinemia shown by the host are due directly to blood loss; others consider the liver fluke as hematophagic and do not regard blood loss as the main factor in causing the pathological changes in the host. These experiments with labeled plasma protein and red cells give strong support to the blood-loss school of thought.

Rabbits infected with 180 larvae and normal rabbits were injected with ^{131}I-labeled serum albumin. The degradation rate of albumin was dramatically greater in the infected animals, but the intravascular pool was only slightly lower than that in the controls. This suggests that synthesis must have kept up with breakdown and implies that synthesis must proceed at a much greater rate in the infected animals. In another experiment, in which infected and normal rabbits were injected with ^{131}I-labeled polyvinylpyrrolidone, there was a significant movement of plasma macromolecules into the gut, presumably via the flukes and bile. The results of this and the previous experiment are most easily explained by direct loss of plasma protein.

Next, infected rabbits injected with ^{51}Cr-labeled red cells showed a substantially shorter half-life for the labeled cells and greater fecal output of radioactivity than did the controls. This again argues for the validity of the blood-loss theory. Infected and normal rabbits injected with ^{95}Nb-labeled albumin and ^{51}Cr-labeled red blood cells at the same time were given an antihelminthic 11 days later. The mean "blood" clearance in the infected animals was 100 times and the mean "plasma" clearance 5 times that of the normal animals; both dropped to normal levels after the antihelminthic treatment. From all these experiments,

evidence is abundant that blood loss is brought about by the flukes.

The hypoproteinemias associated with helminthic infections, especially with gastrointestinal parasites, were investigated by Nielsen[49] (Denmark). Although the ecological, immunological, and therapeutic aspects of intestinal parasitism have been studied extensively in the past decade, little attention has been given to the pathogenesis of secondary manifestations of parasitic gastroenteritis, e.g., the severe hypoproteinemia that occurs with trichostrongylides infections in ruminants and with certain helminthic diseases in man. Although serum proteins labeled with ^{131}I have been used extensively, their digestion in the gastrointestinal tract prohibits their use here. Polyvinylpyrrolidone labeled with ^{131}I has been used because this polymer is not easily absorbed or broken down, and the fecal excretion will indicate the degree of protein leakage.[50] A similar method using ^{59}Fe-labeled iron dextran has been proposed.[51] Because chromium is poorly absorbed in the gastrointestinal tract, ^{51}Cr-labeled albumin has been used in these studies, with the amount of label appearing in the stool indicating the degree of proteinemia.[52] The obvious disadvantage of a slight denaturation, reflected by the short half-life of ^{51}Cr albumin in normal subjects, has led to the suggestion that ^{67}Cu-labeled ceruloplasmin be used in the study of gastrointestinal protein loss.[53]

Infection of cattle in northern Europe with *Ostertagia ostertagi*, the stomach worm, is increasingly important. It occurs in housed cattle during the winter months, presumably caused by larvae absorbed during the autumn. The main clinical observance is diarrhea with emaciation. In chronic cases the plasma albumin fraction is markedly depressed. During the diarrheal phase the cattle are hypercatabolic with short plasma-albumin half-lives, high fractional turnover rates, and high fecal excretion of ^{131}I. However, during the quiescent or convalescence stage, the data indicate a hypocatabolic condition.[54] The pattern of ^{131}I turnover appears to be related to the clinical phases of the disease examined and not to the nature or site of the macroscopic lesions.

Jennings[55] (Scotland) reviewed the isotopic methods that have been used in the study of anemias associated with helminth infections. Many helminth infections are characterized by a concomitant anemia directly attributable to the activities of the parasites and resulting from a partial failure of erythropoiesis, an increase in intravascular destruction of formed red cells, or an abnormal loss of red cells due to hemorrhage.

The first attempt[56] to measure the blood consumed by parasites was made in 1931. Isotopically labeled cells and plasma were first used in 1954 to study *Fasciola hepatica* infection in rabbits[57-59] with ^{32}P-labeled cells and ^{131}I-labeled serum albumin. The ideal label would be one that remains firmly attached to the cell without affecting its life span and is excreted when the cell becomes effete or is destroyed. The red-cell label most closely approximating these conditions is ^{51}Cr, first used in 1950 to estimate circulating red-blood-cell volume.[60] This isotope has been used to detect hemorrhage into the alimentary tract,[61] to obtain a quantitative measure of blood loss due to hookworms in humans,[62] and to obtain a similar measurement in dogs.[63] Recovery rates averaged 96% in humans and 97% in dogs.

When ^{51}Cr-labeled red cells are injected into the cattle, radioactivity during the first 18 to 24 hr declines rapidly to 50 to 70% of initial activity; there follows a slower exponential loss of labeled cells which is still greater than that obtained with other species. Because of this, doubt has been cast on the use of the isotope to study bovine blood loss. However, if the elution rate of chromium is constant in both normal and anemic cows, the experiment would still be valid; the radioactivity in the feces can be related with reasonable accuracy to the blood activity. If the eluted activity is secreted via the bile, an erroneously high estimate will result.

In all circulating half-life studies in the anemic animal, a shortened red-cell life may be due to an increased destruction of red cells, an increased elution rate, or both. If destruction is due to hemorrhage alone, there will be an increased urinary excretion of the label. If the destruction is hemolytic, the effects are additive. Overestimation of red-cell destruction can be avoided with the use of an additional label; the most promising is ^{32}P-labeled diisopropyl fluorophosphate. Gastrointestinal hemorrhage can also be measured indirectly by using labeled plasma protein, preferably simultaneously with labeled red cells. Suitable tracers are ^{51}Cr-labeled plasma albumin, ^{95}Nb-labeled albumin, and ^{67}Cu-labeled ceruloplasmin. Both ^{95}Nb and ^{51}Cr have the disadvantage of altering the half-life of the labeled albumin compared to that measured by ^{131}I-labeled albumin. Because there is normally a substantial movement of plasma albumin into the gut, the use of labeled plasma proteins is perhaps inaccurate, especially when used alone.

Hemoglobin labeled with ^{59}Fe has been used to study the gastrointestinal blood loss caused by *Haemonchus contortus* in sheep.[64] This use was based

on the premise that all the label is lost in the feces, an assumption shown to be false from double-tracer studies[65] using ^{51}Cr and ^{59}Fe. Since anemic animals have an increased requirement for iron, this method is especially doubtful. It has the advantage that no correction for elution has to be made because the normal breakdown of cells in the body releases the iron which is then incorporated into fresh hemoglobin; also, little iron is excreted in the feces.

Labeled compounds incorporated directly into the hemoglobin molecule are necessary to study the failure of the erythropoiesis mechanism; the two most common are ^{59}Fe and glycine-2-^{14}C. The rate at which iron is incorporated into hemoglobin is indicative of the erythropoietic response. These ferrokinetic studies have been used in the human to estimate mean cell life, a red-cell destruction index, a production index based on ^{51}Cr-labeled cells, a plasma-iron turnover rate, and a red-cell-iron turnover rate, but this information on normal domestic animals is largely missing. Variables other than erythropoiesis that influence plasma-iron turnover rate are: dilution of the isotope in enlarged iron stores, synthesis of iron-containing compounds such as myoglobin, and early recycling of ^{59}Fe from rapidly destroyed erythrocytes.

The tracer of choice in studies of erythrocyte survival times is glycine-2-^{14}C because there is little reuse of the label. The technique of in vitro labeling of the immature erythrocytes with either ^{14}C or ^{59}Fe ensures that there is not a prolonged labeling process. These immature cells may, however, have a shorter survival time than normal cells. Tritiated thymidine and autoradiography techniques have been used to study the growth rates of hematopoietic cells,[66] and autoradiography has also been used to study the incorporation of both ^{59}Fe and ^{55}Fe into marrow cells and reticulocytes.[67] If anemia is due to failure of erythropoiesis, this type of investigation will indicate where the failure is occurring. Failure of erythropoiesis can also be due to some extrinsic factor such as iron, folic acid, or vitamin B_{12}. The value of radioactive isotopes to study anemias is indisputable, and by a variation of suitable labels and techniques, all stages in the life of a red cell can be screened.

Hurwitz[68] (Israel) reported the use of labeled reference substances to study intestinal absorption and digestibility. Little attention has been paid to the nutritional–physiological relations between host and parasite. Parasites feed on material taken from the host and may damage the intestinal surfaces, absorb the host's food, suck the host's blood and tissue fluids, cause mechanical obstruction of blood and lymphatic vessels, cause wounds resulting in hemorrhages and the invasion of other pathogenic organisms, and secrete toxins and antienzymes. Parasites may reduce the absorptive capacity of the intestine by damaging the intestinal mucosa or by increasing the passage rate of nutrients through the intestine, leading in severe cases to diarrhea. Absorption has been studied by the classical balance technique, which requires very accurate record of nutrient intake and fecal output. The balance method is considered unsuitable for parasite studies because it usually is designed on a relatively long-term basis. Another approach is to use a single dose of labeled nutrient and measure its disappearance from the intestine, but this technique does not measure net absorption or account for inflow of nutrient from the blood to the intestinal lumen.

Unabsorbable reference substances, labeled or unlabeled, have been used. Unlabeled substances include chromic oxide, polyethylene glycol, and lignin; labels used include ^{91}Y, ^{144}Ce, ^{51}Cr, ^{47}Sc, and ^{140}La. The reference substance is mixed with the feed, and the ratio of nutrient to substance is determined in the feces when steady-state excretion is reached. The expression of percent net absorption is then $100 \times (1 - R_{sample}/R_{diet})$. The advantages of reference substances are: (1) errors are minimized because total fecal collection is not necessary, (2) variations with time after steady state is reached can be studied, and (3) the absorption pattern along the gastrointestinal tract can be followed.

Calcium absorption by laying hens was studied with ^{91}Y and ^{45}Ca. When injected into the upper duodenum, both isotopes moved along the intestine at comparable rates. When both were given orally, the rate of emptying of ^{45}Ca from the stomach was greater than that of ^{91}Y, probably because of adsorption of ^{91}Y by solid particles in the crop and stomach of the hens. This indicates that ^{91}Y is not an ideal reference substance for calcium, although it could be used for estimating net absorption once steady state is reached. When laying hens were fed a diet containing either 1.90 or 3.56% calcium labeled with ^{91}Y and were killed 4 days later, analysis of ligated intestinal segments showed that most calcium absorption occurred in the proximal intestine. Dietary level of calcium had no effect on the percentage of net absorption. Eggshell-formation data showed that calcium absorption was doubled during periods of active shell deposition; calcium absorption in laying hens is evidently closely related to their demand for this mineral.

This experiment demonstrated how reference substances could be used to determine the site of intestinal absorption, the effect of dietary manipulations, and the effect of an almost hour-to-hour change in absorption.

Recommendations

The researchers present at this meeting acknowledged that the recommendations of the last meeting[1] have been implemented, and they requested that these measures be retained and extended. Basic knowledge of immunological phenomenons in parasitic diseases is still lacking, and the acquisition of this information is essential to the useful application of radiation techniques. Further studies are required on in vitro cultivation of infective and pathogenic forms of various parasites and on the metabolism of the parasite itself and of the host–parasite relation, with special reference to nutritional aspects, immunological phenomenons, and pathophysiology.

Immunology

Radioactive isotopes should be used to study the extent of the immunopathological effects of parasitic infections. The reactions could be further studied by using whole-body irradiation, immunosuppressive drugs, and antilymphocyte sera. Differentiation between nonprotective antigens and protective antigens could be carried out with tracers. Parasites themselves could be labeled and followed in the host. The various types of antibodies detected by the usual serological tests could be differentiated to identify, characterize, and separate those which are effective in protection against parasites from those which are responsible for immunopathological events. The differences, if any, between antigens and antibodies at different stages of parasite life cycles can best be studied by isotope techniques. The respective roles of humoral and cellular factors in parasitic infections should be studied with radioactive compounds. The major sites of antigen production and antibody attachment within the parasite could be studied using autoradiographic techniques by labeling antiserums, cells, and metabolic products. The proliferative responses frequently occurring at epithelial and endothelial surfaces in the presence of various parasites should be investigated using cell-culture techniques and radioisotope-labeled precursors of nucleic acids. Whole-body irradiation of animals could be a useful tool to study the several kinetic aspects of host–parasite interactions.

Pathogenic Effects of Parasites

The kinetics of the basic physiology of the host–parasite relation must be studied to assess the pathogenic effects of parasites on their hosts; this is almost impossible to do without using radioisotope techniques. In the developing countries the availability of facilities to carry out kinetic investigations is especially important. Particular attention should be paid to the hypoproteinemias and anemias that often accompany parasitic diseases. The significant leakages of plasma protein that have been demonstrated in several parasitic diseases must be studied in detail, particularly to assess the nutritional effects on the host.

Isotope methods for studying blood-loss anemias are relatively satisfactory, but more work is needed on iron and copper metabolism, autoimmune phenomenons, and other processes associated with red-cell production and destruction. Radioisotope-labeled test substances are needed that can be used for repeated determinations of gastrointestinal leakage so that the different stages of an infection and the diarrheic and quiescent phases of the infection can be investigated. The immunological consequences of gastrointestinal protein leakage must be studied, especially if the increased degradation of immune globulins results in a significant impairment of protective mechanisms. More attention needs to be given to plasma proteins other than plasma albumin, to protein synthesis, and to changes in protein synthesis in parasitized animals. The water and electrolytes exchange in parasitized animals must be studied. The feeding habits, nutrition, and physiology of many parasites and their consequences to the host animal when there is competition for essential nutrients are not well understood and should be investigated. There should be more use of isotopically labeled antiparasitic drugs.

Radiation-Attenuated Vaccines

Table 1 reviews the current status of vaccine development. Specific comments and recommendations follow: (1) The two lungworm vaccines are being more widely accepted in agricultural practice. (2) The irradiated vaccine for hookworms in dogs is likely to be marketed in the near future. Consideration should be given to development of a similar vaccine for man, using apes as laboratory hosts. (3) Laboratory development of vaccine against the gapeworm is proceeding well, and vaccination in the hatchery seems to be the best practical solution. (4) Because of its zoonotic significance for many countries, the preliminary experiment giving 92% protection against *Echinococcus*

Table 1 Review of Status of Radiation-Attenuated Vaccines

Parasite	Vaccine status
Helminths	
Dictyocaulus viviparus	In commercial use
Dictyocaulus filaria	In commercial use
Ancylostoma caninum	Promising commercial application
Syngamus trachea	Promising commercial application
Echinococcus granulosus	Encouraging laboratory results
Schistosoma spp.	Further study needed
Fasciola spp.	Further study needed
Human hookworms	Further study needed
Haemonchus and other gastrointestinal nematodes	Further study needed
Protozoa and other organisms	
Plasmodium spp.	Encouraging laboratory results
Trypanosoma spp.	Further study needed
Anaplasma spp.	Further study needed
Babesia spp.	Further study needed
Theileria spp.	Further study needed

should be followed up. (5) Although results do not justify immediate application of irradiated vaccines to humans, the work on various laboratory hosts with *Schistosoma mansoni* and *Schistosoma japonicum* is encouraging. (6) The possibility of using irradiated vaccine against liver flukes should be explored further because of the widespread distribution and economic significance of these parasites. (7) The development of a satisfactory vaccine against *Haemonchus contortus* is delayed by the unresponsive period shown in lambs. This is of considerable immunological interest. (8) Preliminary results of irradiated vaccines against malaria are promising; research should be continued. Irradiation studies should be encouraged against *Trypanosoma, Anaplasma,* and *Babesia.* Vaccines against *Theileria* spp. should be investigated, since prophylaxis depends entirely on vector control at present.

Recommendations on Irradiation

Comparison of various ionizing radiations should be considered. New information on physical constants during irradiation (temperature of medium, oxygen tension, etc.) should be used. The biological phenomenon of increased infectivity of nematode larvae after low-dose irradiation should be investigated. Basic mechanisms of radiation damage to helminths and the apparently superior immunogenic efficacy of irradiated larvae should be studied. In vitro cultivation and biochemical tests might be considered as methods for investigating radiation attenuation. Long-term storage studies of helminth larvae and protozoa should be made to facilitate the development of irradiated vaccines. (F. E. McKinney)

References

References marked with an asterisk were cited by the author but were not available to the Isotopes Information Center for bibliographic verification.

1. *Production and Utilization of Radiation Vaccines Against Helminthic Diseases,* Report of a Panel Meeting, Vienna, Dec. 16–18, 1963, International Atomic Energy Agency, Vienna, 1964 (STI/DOC/10/30).
2. *Advisory panel meeting on Use of Isotopes and Radiation in Animal Sciences, 1965, unpublished.
3. I. Varga, Immunization Experiments with Irradiated Larvae of *Syngamus trachea* in Chickens, in *Isotopes and Radiation in Parasitology,* pp. 1-11, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
4. T. A. Miller, Development of an X-Irradiated Vaccine for Ancylostomiasis, in *Isotopes and Radiation in Parasitology,* pp. 13-15, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
5. *T. A. Miller, Effect of X-Irradiation upon the Infective Larvae of *Ancylostoma caninum* and the Immunogenic Effect in Dogs of a Single Infection with 40-kr Irradiated Larvae, *J. Parasitol.*, **50**: 735 (1964).
6. *T. A. Miller, Studies on Canine Ancylostomiasis: Double Vaccination with X-Irradiated *Ancylostoma caninum* Larvae, *J. Amer. Vet. Med. Ass.*, **146**: 41 (1965).
7. *T. A. Miller, Effect of Route of Administration of Vaccine and Challenge on the Immunogenic Efficiency of Double Vaccination with Irradiated *Ancylostoma caninum* Larvae, *J. Parasitol.*, **51**: 200 (1965).
8. *T. A. Miller, Persistence of Immunity Following Double Vaccination of Pups with X-Irradiated *Ancylostoma caninum* Larvae, *J. Parasitol.*, **51**: 705 (1965).
9. B. Fitzpatrick and W. Mulligan, Variables in the Radiation-Attenuation of Helminth Larvae: Temperature/Oxygen Effects, in *Isotopes and Radiation in Parasitology,* pp. 17-19, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
10. Z. Prochazka and J. Tomanek, Some Practical Aspects on the Production of Radiation Vaccines Against Helminthic Diseases, in *Isotopes and Radiation in Parasitology,* pp. 21-33, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).

11.*F. W. Jennings, W. Mulligan, and G. M. Urquhart, Variables in X-ray "Inactivation" of *Nippostrongylus brasiliensis* Larvae, *Exp. Parasitol.*, **13**: 367 (1963).
12. G. M. Urquhart, W. F. H. Jarrett, F. W. Jennings, W. I. M. McIntyre, and W. Mulligan, Immunity to *Haemonchus contortus* Infection: Relationship Between Age and Successful Vaccination with Irradiated Larvae, *Amer. J. Vet. Res.*, **27**: 1645-1648 (1966).
13. G. M. Urquhart, Immune Response of Young Animals to Infection with X-Irradiated and Normal Nematode Larvae, in *Isotopes and Radiation in Parasitology*, pp. 35-41, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
14.*G. M. Urquhart, Development of Irradiated Vaccines Against Helminthic Diseases, in *Production and Utilization of Radiation Vaccines Against Helminthic Diseases*, pp. 11-15, Report of a Panel Meeting, Vienna, Dec. 16–18, 1963, International Atomic Energy Agency, Vienna, 1964 (STI/DOC/10/30).
15. E. H. Sadun, J. S. Williams, C. Witherspoon, and L. K. Martin, Relative Role of Eggs and Adult Worms in Development of Liver Damage in Mice Infected with *Schistosoma mansoni*, in *Isotopes and Radiation in Parasitology*, pp. 43-58, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
16.*R. Jaffe, Sobre la patogenia de las lesiones anatomo pathologicas bilharzianas, *Rev. Policlín. Caracas*, **9**: 3321-3345 (1940).
17.*H. B. Day, Pulmonary Schistosomiasis by Erfan, M., *Trans. Roy. Soc. Trop. Med. Hyg.*, **42**: 114-115 (1948).
18.*A. Halawani and M. M. Dawood, Recent Advances in the Treatment of Bilharziasis. II. Maracil D., *J. Egypt. Med. Ass.*, **33**: 463-480 (1950).
19.*A. Abdallah and M. Saif, Tracer Studies with Antimony-124 in Man, in *Ciba Foundation Symposium on Bilharziasis, London, 1962*, pp. 287-309.
20.*T. Gillman, Venous Obstruction in the Pathogenesis of Hepatic Bilharziasis. A Preliminary Report of Comparative Findings in Rats, Monkeys, and Man, *Ann. Trop. Med. Parasitol.*, **51**: 409-416 (1957).
21.*A. H. Mousa, *Ciba Foundation Symposium on Bilharziasis, London, 1962*, pp. 63-64.
22.*M. Z. A. Souidan, Some Immediate Side Effects of Antibilharzial Treatment, presented at the International Symposium on Bilharziasis, May 1962, Cairo (held by UAR Science Council).
23.*M. Hashem, The Aetiology and Pathogenesis of the Endemic Form of Hepatosplenomegaly "Egyptian Splenomegaly," *J. Egypt. Med. Ass.*, **30**: 48-59 (1947).
24.*L. Bogliolo, Subsidios para o conhecimento da forma hepato-esplenica e da forma toxêmica da esquistossomose mansonica, p. 301, Serviço Nacional de Educação Sanitaria, Rio de Janeiro, Brazil, 1958.
25.*H. M. Salem, *Ciba Foundation Symposium on Bilharziasis, London, 1962*, pp. 65-67.
26.*E.H. Sadun, J. S. Williams, F. C. Meroney, and J. F. Mueller, Biochemical Changes Induced in Mice by Infection with the Plerocecoid Larvae of the Cestode, *Spirometra mansonoides*, *J. Parasitol.*, **51**: 532-536 (1965).
27.*M. G. Radke and E. H. Sadun, Resistance Produced in Mice by Exposure to Irradiated *Schistosoma mansoni* Cercariae, *Exp. Parasitol.*, **13**: 134-142 (1963).
28.*C. R. Lambert, Chemotherapy of Experimental *Schistosoma mansoni* Infections with Nitrothiazole Derivative Ciba 32, 644 Ba, *Ann. Trop. Med. Parasitol.*, **58**: 292-303 (1964).
29. B. T. Wellde and E. H. Sadun, Resistance Produced in Rats and Mice by Exposure to Irradiated *Plasmodium berghei*, in *Isotopes and Radiation in Parasitology*, pp. 59-73, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
30. E. H. Sadun, Immune Mechanisms in Mice Immunized with Irradiated *Plasmodium berghei*, in *Isotopes and Radiation in Parasitology*, p. 75, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
31. M. P. Cunningham and E. B. Grainge, Immune Response of Cattle Infected with *Trypanosoma brucei* Subgroup and the Antigenic Variation of Infecting Organisms, in *Isotopes and Radiation in Parasitology*, pp. 77-88, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
32.*A. R. Gray, *Ann. Trop. Med. Parasitol.*, **56**: 4-13 (1962).
33.*H. E. Hornby, S. A. Evans, and R. L. Cornell, Tanganyika Territory, Department of Veterinary Science and Animal Husbandry, Annual Report for 1933, pp. 34-36 (1934).
34.*W. H. R. Lumsden, 1st International Conference on Wildlife Disease, Sha-Wan-Ga Lodge, High View, N. Y., June 1962.
35. M. P. Cunningham, Vaccination of Cattle Against Trypanosomes by Infection and Treatment, in *Isotopes and Radiation in Parasitology*, pp. 89-91, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
36. A. Sokolić, Immunological Studies on *Fasciola hepatica;* Clinical and Immunological Response in Mice to Infection with Irradiated and Normal Fluke Cysts, in *Isotopes and Radiation in Parasitology*, pp. 93-103, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
37.*B. Dawes and D. L. Hughes, Fascioliasis: The Invasive Stages of *Fasciola hepatica* in Mammalian Hosts, in *Advances in Parasitology*, Vol. 2, p. 97, B. Dawes (Ed.), Academic Press Inc., New York, 1964.
38.*I. G. Kagan, Mechanisms of Immunity in Trematode Infections, in *Biology of Parasites*, p. 277, E. J. L. Soulsby (Ed.), Academic Press Inc., New York, 1966.
39.*E. J. L. Soulsby, Trematodes of Sheep and Goats, in *Textbook of Veterinary Clinical Parasitology*, Vol. 1, p. 517, Blackwell, Oxford, 1965.
40. L. Casarosa, Effects of Total- (Partial-) Body Irradiation on Helminthic Infections, in *Isotopes and Radiation in Parasitology*, pp. 105-115, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
41.*L. Hektoen, *J. Infect. Dis.*, **22**: 28-33 (1915).

42. W. H. Taliaferro, L. G. Taliaferro, and B. N. Jaroslow, *Radiation and Immune Mechanisms*, Academic Press Inc., New York, 1964.
43.*N. Gengozian and T. Makinodan, Relation of Primary Antigen Injection to Time of Irradiation on Antibody Production in Mice, *J. Immunol.*, **80**: 189-197 (1958).
44.*E. L. Tyzzer and J. A. Honeij, The Effects of Radiation on the Development of *Trichinella spiralis* with Respect to Its Applications to the Treatment of Other Parasitic Diseases, *J. Parasitol.*, **3**(2): 43-56 (1916).
45.*R. E. Duxbury and E. H. Sadun, *Proc. Helminthol. Soc. Wash. D.C.*, **30**(2): 263-265 (1963).
46. A. Yarinsky, The Influence of X-Irradiation on the Immunity of Mice to Infection with *Trichinella spiralis*, *J. Elisha Mitchell Sci. Soc.*, **78**: 29-43 (1962).
47. R. D. Stoner and W. M. Hale, Effect of Cobalt^{60} Gamma Radiation on Susceptibility and Immunity to Trichinosis, *Proc. Soc. Exp. Biol. Med.*, **80**: 510-512 (1952).
48. J. MacLean, P. H. Holmes, J. D. Dargie, and W. Mulligan, Pathophysiology of *Fasciola hepatica* Infections, in *Isotopes and Radiation in Parasitology*, pp. 117-123, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
49. K. Nielsen, Hypoproteinemias Associated with Helminthic Infections, with Special Reference to Gastro-Intestinal Parasites, in *Isotopes and Radiation in Parasitology*, pp. 125-132, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
50. R. S. Gordon, Jr., Exudative Enteropathy. Abnormal Permeability of the Gastrointestinal Tract Demonstrable with Labelled Polyvinylpyrrolidone, *Lancet*, No. 7068, 1959, **1**: 325-326 (Feb. 14, 1959).
51. S. B. Andersen and S. Jarnum, Gastrointestinal Protein Loss Measured with ^{59}Fe-Labelled Iron-dextran, *Lancet*, No. 7446, 1966, **1**: 1060-1062 (May 14, 1966).
52. T. A. Waldmann, Gastrointestinal Protein Loss Demonstrated by ^{51}Cr-Labelled Albumin, *Lancet*, No. 7194, 1966, **2**: 121-123 (July 15, 1961).
53. T. A. Waldmann and R. D. Wochner, The Measurement of Gastrointestinal Protein Loss by Means of ^{51}Cr-Albumin and ^{67}Cu-Caeruloplasmin, in *Radioisotope Techniques in the Study of Protein Metabolism*, pp. 171-181, Panel Report, Vienna, June 1–5, 1964, International Atomic Energy Agency, Vienna, 1965 (STI/DOC/10/45).
54.*K. Nielsen, *Gastrointestinal Protein Loss in Cattle. A Clinical and Pathophysiological Study*, C. F. Mortensen, Copenhagen, 1966.
55. F. W. Jennings, Anaemias Associated with Helminthic Infections, in *Isotopes and Radiation in Parasitology*, pp. 133-140, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).
56.*H. S. Wells, *J. Parasitol.*, **17**: 167 (1931).
57.*F. W. Jennings, I. M. Lauder, W. Mulligan, and G. M. Urquhart, *Vet. Rec.*, **66**: 155 (1954).
58.*F. W. Jennings, W. Mulligan, and G. M. Urquhart, *Trans. Roy. Soc. Trop. Med. Hyg.*, **49**: 305 (1955).
59.*F. W. Jennings, W. Mulligan, and G. M. Urquhart, *Exp. Parasitol.*, **5**: 458 (1956).
60. S. J. Gray and K. Sterling, The Tagging of Red Cells and Plasma Proteins with Radioactive Chromium, *J. Clin. Invest.*, **29**: 1604-1613 (1950).
61. C. A. Owen, Jr., J. L. Bollman, and J. H. Grindlay, Radiochromium-Labeled Erythrocytes for the Detection of Gastrointestinal Hemorrhage, *J. Lab. Clin. Med.*, **44**: 238-245 (1954).
62.*M. Roche, *Lancet*, **1**: 965 (1956).
63.*C. H. Clark, J. M. Kling, C. H. Woodley, and N. Sharp, A Quantitative Measurement of the Blood Loss Caused by Ancylostomiasis in Dogs, *Amer. J. Vet. Res.*, **22**: 370 (1961).
64. J. R. Georgi, Estimation of Parasitic Blood Loss by Whole-Body Counting, *Amer. J. Vet. Res.*, **25**: 246-250 (1964).
65.*C. H. Clark, G. K. Kiessel, and C. H. Goby, *Amer. J. Vet. Res.*, **23**: 977 (1962).
66. B. Clarkson, T. Ohkita, K. Ota, and J. Fried, Studies of Cellular Proliferation in Human Leukemia. I. Estimation of Growth Rates of Leukemic and Normal Hematopoietic Cells in Two Adults with Acute Leukemia Given Single Injections of Tritiated Thymidine, *J. Clin. Invest.*, **46**: 506-529 (1967).
67. J. H. Fowler, E. A. McCulloch, J. E. Till, and L. Siminovitch, An Improved Method for Radioautography of Erythropoietic Cells Labelled with Fe^{55} or Fe^{59}, *J. Lab. Clin. Med.*, **68**: 523-530 (1966).
68. S. Hurwitz, Use of Labelled Reference Substances in Studies on Intestinal Absorption and Digestibility, in *Isotopes and Radiation in Parasitology*, pp. 141-146, Proceedings of Research Coordination Meeting, Vienna, July 31–August 4, 1967, International Atomic Energy Agency, Vienna, 1968 (STI/PUB/181).

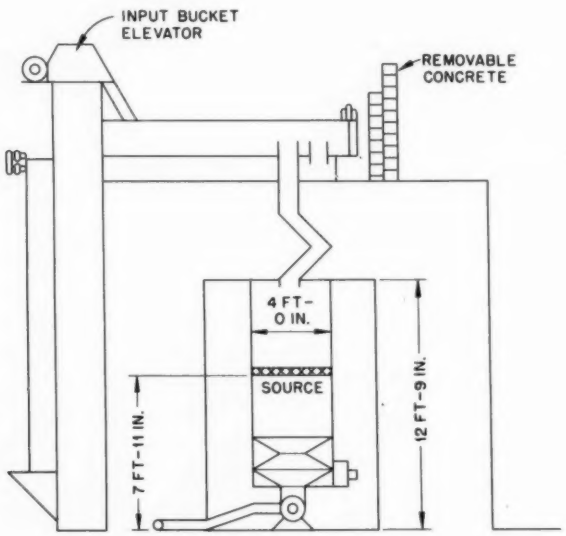
New Radiation-Chemical Synthesis in Australia

A new product made by radiation-chemical synthesis is about to be marketed in Australia.* The radiation source used is a 2000-curie ^{60}Co unit. The product, Protapol DI, is a solid-state reagent for the radioimmunoassay of hormones and specific proteins by a method developed by Dr. Kevin Catt and Dr. Hugh Niall of the Department of Medicine, Monash University, Prince Henry's Hospital, Melbourne, which has brought the assay of hormones within the scope of routine clinical testing. The reagent, a graft copolymer, is a form of poly(tetrafluoroethylene-g-isothiocyanato styrene). (MG)

At. Energy Aust., 10(2): 17 (1968).

Grain-Irradiator Design

At the Third Symposium* of the Kanto Area of the Japan Food Irradiation Research Council, in July 1966, interest was shown in two U. S. food-irradiation devices†: a mobile irradiator with a 1.28×10^5-curie ^{60}Co source for treating strawberries, for example, with a dose of 1.75 to 2.25×10^5 rads at a rate of 1000 lb/hr; and a stationary irradiator with a 2.6×10^4-curie source for treating bulk grain with a dose of 2.5×10^4 rads at a rate of 5000 lb/hr. With the stationary installation (Fig. 1) are



included a conveyor and hopper. Construction and installation costs are estimated as $225,500 for the mobile irradiator and $229,480 for the stationary.

(Kenzo Mori of JAERI, on temporary assignment to ORNL)

*T. Shigematsu, Measurement of Radiation Doses and Food Irradiation Facilities (in Japanese), paper at 3rd Kanto Area Symposium, Japan Food Irradiation Research Council, July 19, 1966.

†*a.* Preliminary Design Report, Title I, Mobile Gamma Irradiator, USAEC Report KLX-1866, Vitro Engineering Company, 1964.

b. Preliminary Design Report, Title I, Bulk Grain Irradiator, USAEC Report KLX-1869, Vitro Engineering Company, 1965.

Isotopes in Entomology

Isotopes and Radiation in Entomology, Symposium Proceedings, Vienna, 1967 (STI/PUB/166)(428 pp.; $9.00).

Control of Livestock Insect Pests by the Sterile-Male Technique, Panel Proceedings, Vienna, 1967 (STI/PUB/184)(102 pp.; $3.00).

Radiation, Radioisotopes and Rearing Methods in the Control of Insect Pests, Panel Proceedings, Tel Aviv, 1966 (STI/PUB/185)(148 pp.; $4.00).

Three "proceedings" published by the IAEA (Vienna) in 1968 will be of interest to entomologists as well as to agriculture, forestry, animal husbandry, and public-health workers. Insects discussed at the several meetings include bees, aphids, ticks, tsetse flies, weevils, beetles, mosquitoes, locusts, and fruit and vegetable flies. Radioisotope-tracer techniques were used in tracking insects as well as tracing insecticides, and both irradiation and chemicals as sterilizing agents were investigated. Among the plant crops affected by the insects considered are onions, beets, corn, sugarcane, cotton, coffee, dates, cherries, and citrus fruit. (MG)

Mutations in Plant Breeding

The second* meeting on the Co-ordinated Programme of Research on the Production and Use of Induced Mutations in Plant Breeding was held Sept. 11–15, 1967, in Vienna and attended by 24 scientists from 14 countries. The program was initiated in 1965 as a joint FAO–IAEA effort and held its first† meeting in January 1966.

At the second meeting, participants and FAO–IAEA staff members presented 22 papers reporting on work done, discussed the various projects in progress, and reviewed and revised the technical recommendations prepared at the first meeting. In the 2-year interval between the meetings, a dozen new, named varieties of crops were developed using nuclear radiation and chemicals. Nine of the new strains are already being grown commercially: early maturing soybeans and better yielding rice in Japan; a larger and early ripening peach in Argentina; higher protein amber-colored wheat in India; two high-yielding varieties of durum wheat in Italy; improved barley in the United Kingdom; and improved barley and chrysanthemums in the United States of America. An improved wheat is to be grown in Argentina and barley in Sweden.

Except for the American barley, all are the result of mutations induced by nuclear radiation. The Argentine peach was produced by chronic exposure of seeds to gamma radiation. The Swedish barley resulted from crossing a mutant produced by X rays with a standard variety. The Italian wheats were produced with thermal-neutron radiation, and the British barley, with gamma radiation. The American barley was developed with radiomimetic chemicals.

Two other related IAEA publications are: *Effects of Low Doses of Radiation on Crop Plants,* Report of a Panel Meeting, Rome, 1964, Technical Reports Series, No. 64, International Atomic Energy Agency, Vienna, 1966 (STI/DOC/10/64); and *Neutron Irradiation of Seeds,* Technical Reports Series, No. 76, International Atomic Energy Agency, Vienna, 1967 (STI/DOC/10/76) [reviewed in *Isotopes and Radiation Technology,* 5(4): 313-314 (Summer 1968)]. (MG)

**Mutations in Plant Breeding. II,* Panel Proceedings, Vienna, 1967, International Atomic Energy Agency, Vienna (STI/PUB/182).

†*Mutations in Plant Breeding,* Panel Proceedings, Vienna, 1966, International Atomic Energy Agency, Vienna, 1966 (STI/PUB/129).

Rice Breeding with Induced Mutations*

Rice is the staple diet of roughly half of mankind. A joint FAO–IAEA program to produce more and better rice was initiated in 1964. The third meeting of the participants, June 5–9, 1967, was attended by scientists from nine countries and three international organizations. Twelve papers reported on mutations induced in rice by the use of chemicals and/or radiation and related subjects.

Discussions at the meeting indicated that X, gamma, and neutron radiations as well as chemicals should be used to induce mutations. For ionizing-radiation treatment, the use of dormant seeds with a moisture content of 12 to 13% was recommended. The optimum radiation doses suggested were 15 to 30 krads for X or gamma radiation and about 10% of this amount for neutron radiation. Several chemicals were suggested. Combined radiation-chemical treatments were discussed, but too little information was available for any conclusion to be reached.

The results of rice cultivation and harvesting tests carried out in 1966–1967 on various mutants are reported. (MG)

*Summary of Technical Report 86, Report of FAO/IAEA Research Co-ordination Meeting on the Use of Induced Mutations in Rice Breeding, Taipei, 1967.

Radiation Pasteurization of Gulf Shellfish

By A. F. Novak and J. A. Liuzzo
USAEC Report ORO-660, Annual Report, January 1–December 31, 1967
January 30, 1968 (CFSTI, $3.00, 40 pp.)

Research during previous years of this contract showed that irradiation of Gulf shrimp and oysters at doses of 50 to 200 krads extended shelf life 5 to 21 days. Results in 1967 continue to affirm the feasibility of radiation pasteurization to extend the shelf life of iced Gulf shellfish. Tests to determine accurately the freshness of the product before irradiation have been investigated because one of the requisites for successful application of the method is a fresh product. Measurements of viscosity of shrimp homogenate and of the concentration of carbonyls show promise and, if perfected, may serve as methods to study the changes that occur during and after irradiation.

Studies with bacteria that survive low-level radiation continue to show a reduction of synthesis of undesirable by-products by the bacteria during storage of oysters. In the past, the reduction has been ascribed to the decrease in numbers of bacteria; however, data presented here show that when oyster homogenate was inoculated with equal numbers of irradiated and nonirradiated bacteria, reduction in by-product synthesis was still evident. Results of another study showed that low-level radiation does not alter the proximate composition of oysters. Crude protein was the only nutrient significantly affected. In some instances, decreases were observed for ash, nonprotein nitrogen, and true protein. Ash and glycogen content were significantly reduced by iced storage. Emphasis of future work will be on shipping studies and on education of industrial executives. (FEM)

Section
IV
Isotopes and Radiation Technology

Isotopes Around the World

First ^{242}Cm Isotope Battery in Europe*

On July 5, 1968, an isotope battery, the energy for which is derived from the radioactive alpha decay of the isotope ^{242}Cm (3320 curies/g), went into operation at the European Transuranium Institute. This isotope battery (Fig. 1) is the first of its kind in Europe. In the United States, however, two curium batteries have so far been commissioned as part of the space program. Their salient feature is a favorable power/weight ratio.

The isotope battery does not owe its origin to any special and costly research program but came into being because a series of experiments under the institute's transplutonium program had to be broken off. In March 1967 the institute had started on the irradiation of 13 g of americium in the BR-2 reactor at Mol, Belgium, with the aim of producing about 100 mg of ^{244}Cm and traces of californium. Curium-244 is a

*Reprinted, with minor editorial changes, from *Euratom*, 7(3): inside back cover (September 1968); written by engineers of the European Transuranium Institute, Karlsruhe, Germany.

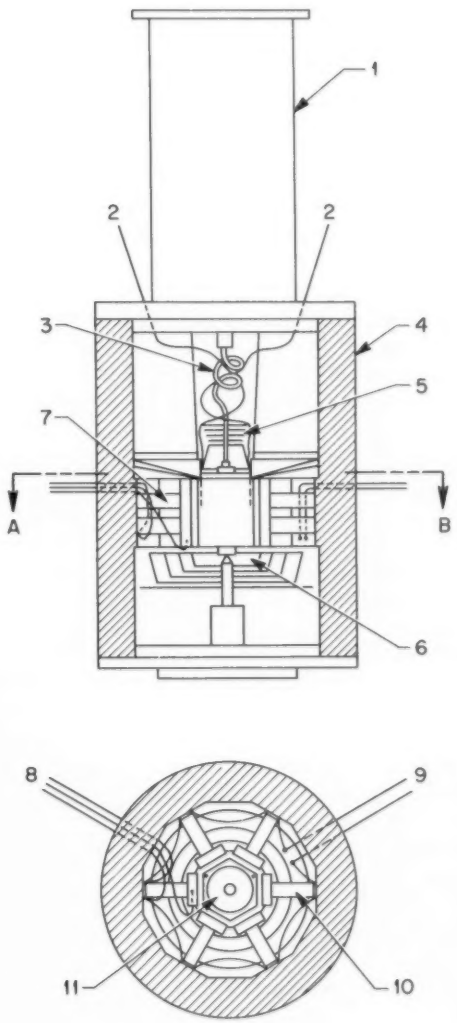


Fig. 1 Diagram of ^{242}Cm isotope battery. The curium, as the oxide, is enclosed in a small double-walled platinum capsule, which is heated by the decay heat. The capsule is under vacuum in a copper housing, which is equipped with shielding and thermal-insulation material as well as with six Si–Ge thermocouples. One leg of each thermocouple is heated by the hot capsule, and the other is connected to the housing and cooled. Thus the heat generated by the alpha decay is partially converted to useful electric current. The thermoelectric section of the isotope battery was supplied by Allgemeine Elektrizitäts Gesellschaft (AEG). (1) Gas compensation tank; (2) measuring thermocouples; (3) capillary tube for drawing off helium (alpha decay generates helium atoms); (4) housing; (5, 6) radiation shielding; (7) midsection packed with glass wadding; (8) measuring thermocouples; (9) current discharge; (10) power thermocouples; and (11) curium container.

relatively stable isotope (half-life 18 years) and therefore suitable for various types of scientific research. Through causes that have not yet been clarified, the can of one of the capsules inserted in the reactor for irradiation developed a leak, and irradiation had to be suspended. This occurred at a time when the ^{242}Cm concentration was relatively high but the ^{244}Cm concentration still very low.

In early 1968 the irradiated capsules were returned to the institute for examination of the can damage. For various reasons, however, the obvious course—separation and transfer of the curium to another capsule and resumption of the irradiation process—could not be adopted. The enforced interruption of irradiation operations offered a good opportunity to conduct a searching inquiry into all problems arising in connection with the handling of fairly large quantities of highly alpha-active and neutron-emitting material and to gain valuable know-how. Such experience is valuable not only from the standpoint of producing transuranium elements with higher atomic numbers but also from that of research into the physical and chemical properties of many of these elements—work which occupies a leading place in the institute's program. Since there could be no reirradiation here, the obvious course was to recover the ^{242}Cm and encapsulate it to make a small heat source that, together with a suitable thermocouple rig, would form an isotope battery. The additional expenditure was comparatively small, especially as AEG undertook to construct the center section of the battery with the thermocouples. The most important result of the work, the acquisition of know-how, was thus enhanced by the construction of an isotope battery.

All operations, such as purification of the irradiated material; design, construction, and filling of the heating capsule; design and construction of the other battery parts; and all preliminary experiments and preparations, were completed inside 6 months, one of the reasons being the urgency due to the short half-life of ^{242}Cm. Under these conditions it was not possible to optimize various parameters, such as efficiency and weight. However, it can be stated that the facilities available at the institute make it possible to handle ^{242}Cm in quantities of the order of several grams and that the technology of isotope battery construction is being mastered.

(MG)

Section V

Isotopes and Radiation Technology

Process Radiation Development

Technical Progress in Wood-Polymer and Other Fiber-Polymer Combinations Around the World

By William E. Mott* and Vivian T. Stannett†

Editor's Note: W. E. Mott and V. T. Stannett both attended and presented papers at the November 1967 IAEA-sponsored study group on polymer-containing fibrous materials in Bangkok. Mott was chairman of the meeting. Mott also attended and presented a paper at the May 1968 Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry, sponsored by the Finnish AEC.

Abstract: *The worldwide activities on wood–polymers and other polymer-containing fibrous materials are reported, with emphasis on the technical rather than the economic and natural-resources aspects of the subject.*

During the past 18 months there have been two important international meetings on wood–polymers and related materials. One, a study group on polymer-containing fibrous materials sponsored by the International Atomic Energy Agency (IAEA), was held in Bangkok in November 1967.‡ Of the 39 participants and observers, 22 were from countries of the Far East (Australia, India, Japan, Korea, Philippines, Taiwan, Thailand, and South Vietnam), 9 from countries of the Western Hemisphere (Canada, Finland, West Germany, Sweden, the United Kingdom, and the United States), and 8 from international organizations (Economic Commission for Asia and the Far East, Food and Agriculture Organization, International Atomic Energy Agency, and United Nations industrial development organizations). The general purposes of this study group were to review the technology of polymer-containing fibrous materials, which has developed during the last 6 years; to assess the fibrous resources of the Far East and the potential markets for impregnated products; and to recommend to the IAEA the research and development program best suited to exploit the resources and meet the needs of the developing countries of the Far East.

The second meeting took place in Helsinki in May 1968. This Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry,§ sponsored by the Finnish Atomic Energy Commission, the University of Helsinki, the Central Association of Finnish Woodworking Industries, the Finnish Plastics Association, the Finnish Pulp and Paper Research Institute, and the Association for Power and Fuel Economy (EKONO), attracted more than 200 scientists to its 2-day program. Four countries outside of Scandinavia were represented: Canada, Hungary, the United Kingdom, and the United States. The aim of this symposium was to inform the Scandinavian wood-processing industry of results obtained by Scandinavian laboratories on the application of plastics to improve the quality of wood and wood-fiber products and to bring the industry up to date on the status of wood–polymer research and development outside Scandinavia.

The papers and discussions presented at these two meetings provide the framework for this report on the activities around the world on wood–polymers and other polymer-containing fibrous materials. Reference

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†Professor of Chemical Engineering, Department of Chemical Engineering, North Carolina State University, Raleigh, N. C.

‡The full proceedings have been published by the IAEA.

§Proceedings have been published by the Department of Radiochemistry, University of Helsinki.

is made to a number of other recent publications as required to complete the picture. In general, the emphasis is on the technical rather than the economic and natural-resources aspects of the subject.

North America

Canada

The Canadian studies of radiation-produced wood–polymers were initiated in 1960 at McMaster University with emphasis on the grafting of styrene to cellulose.[1] Beginning in about 1964 Atomic Energy of Canada Limited set about to determine the physical properties of materials radiation-produced by the homopolymerization process from Canadian species of sugar maple, yellow birch, pine, aspen, eastern white spruce, basswood, and cedar.[2] Three monomer systems were used: methyl methacrylate with diallyl phthalate (90:10); styrene with acrylonitrile (60:40) plus 2% divinyl benzene; styrene with acrylonitrile (60:40) plus 10% vinyl pyrrolidone. All specimens were irradiated to 2 Mrads, a dose which was found to polymerize these systems completely. The impregnation and polymerization steps were performed in the same vessel, eliminating the necessity of wrapping the test specimens in aluminum foil.

Changes in the following properties over untreated controls were determined as a function of polymer loading: static bending, compression parallel to grain, toughness, hardness, abrasion, and water absorption and desorption. Although results varied somewhat with wood species and polymer type, in general the greatest improvements were found in compression strength, hardness, and water absorption. Some improvements were reported in static bending, but essentially no improvements in toughness and abrasion resistance.

During this investigation of properties, an interest developed in dose-rate effects and in the radiation dose to achieve complete polymerization of monomers in various woods. In attempts to obtain good data on the reaction kinetics by direct determination of the amount of polymer formed, considerable scatter of the results was observed. This scatter was related to (*a*) sample-to-sample variations in the wood, (*b*) sample-to-sample variations in monomer loading, (*c*) post-irradiation polymerization during heating to remove unreacted monomer from the wood, and (*d*) incomplete removal of monomer from highly converted samples. In addition, the direct method of measuring polymer was considered too laborious and suitable only for ovendry specimens. A method based on the temperature rise during polymerization, measured by means of a thermocouple embedded in the impregnated wood samples, was therefore adopted.[3] Some observations from this study[3,4] were:

1. The highest temperature reached in a run corresponds to complete polymerization. As expected, higher peak temperatures are reached at higher loadings because more heat is produced during the polymerization. Also, for a given loading, the lower the dose rate, the lower the peak temperature. For example, in birch at 83% loading of methyl methacrylate and a dose rate of 0.26 Mrad/hr, the peak temperature is about 130°C, whereas at a 43% loading it is only about 85°C. Upon decreasing the dose rate by a factor of 10, the peak temperature drops to about 90°C at the 83% loading, to about 60°C at the 43% loading.

2. The dose required for complete polymerization of methyl methacrylate in pine and birch is decreased by higher monomer loadings (from about 1 Mrad to about 0.6 Mrad as loading increases from 43% to 83% at a dose rate of 0.26 Mrad/hr) and lower dose rates. The dose for complete polymerization in birch is a function of the dose rate to the 0.45 power at a 43% loading, to the 0.38 power at an 83% loading.

3. Other factors being equal, the temperature rise at any delivered dose can be related to the percent conversion of the monomer.

4. In wood, the polymerization reaction accelerates continuously to about 80% conversion, followed by a slower reaction rate to complete conversion.

Davies[4] has indicated that, by refining the temperature-rise technique, it will be possible to examine other reaction variables and to determine optimum design parameters and processing conditions for wood–polymer irradiators.

The various aspects in the design of a plant for polymerizing monomers in fibrous materials were reviewed by Felice[5] for the Bangkok meeting. He concluded that the maximum radiation efficiency attainable is about 15%, leading to a total impregnation-plus-irradiation cost for a polymethyl methacrylate product of about 1.3 cents/Mrad-lb.

United States

With the publication in the next few months of final reports at West Virginia University[6] and Research Triangle Institute,[7] the USAEC (Division of Isotopes Development) will complete the research and development program on wood–polymer materials currently in progress. Activities in the United States are now

directed primarily to product development, particularly of flooring, and are proceeding under industrial sponsorship.

The commercial production of wood–polymer materials in the United States began about 3 years ago. Three companies (American Novawood Corporation, Atlantic Richfield Company, and Lockheed-Georgia Company) are currently using radiation to cure monomer-impregnated wood; another (Radiation Machinery Corporation) has recently announced plans for installing an irradiator for wood–polymer production. At least two companies [American Machine & Foundry Company (AMF) and the previously mentioned American Novawood Corporation] are effecting polymerization by thermal-catalytic means.

The American Novawood Corporation (Lynchburg, Va.) is presently manufacturing a line of parquet flooring called Gammapar in four wood species (red oak, white oak, maple, and walnut) and in a variety of colors. Gammapar has been specified for use in the Kansas City International Airport in which there is to be over 10 acres of flooring. Other American Novawood products for the building market include stair treads, risers, thresholds, and doorsills. Veneer panels have been produced on an experimental basis in sizes up to 24 by 66 in.; thicknesses have been as low as $\frac{1}{40}$ in. The surface evaporation problem is said to have been reduced to a point where the $\frac{1}{40}$-in.-thick material can be sanded and polished without sand-through. However, the yield is quite low owing to brittleness, color nonuniformities, and other defects. The American Novawood facility is licensed for 400 kilocuries of ^{60}Co.

The Atlantic Richfield Company (Philadelphia, Pa.) has its production operations at the Nuclear Materials and Equipment Corporation (NUMEC), a wholly owned subsidiary. The major product, a prefinished parquet-panel flooring named PermaGrain, is cured in a cobalt irradiator. PermaGrain contains a fire retardant and is reported to exhibit qualities superior to natural red oak, 100% vinyl, and epoxy terrazzo. Normal dimensions of one panel are 12 by 12 by $\frac{5}{16}$ in. The current production rate is about 4000 sq ft/week. Production in 1969 could exceed a million square feet.

Technical and marketing development activities on wood–polymer materials have been under way at the Lockheed-Georgia Company (Marietta, Ga.) for over 3 years. The production capacity at Lockheed-Georgia is estimated to be 250,000 bd ft/year using the 200-kilocurie ^{60}Co irradiator installed in 1967. This effort, although involving considerable research and development, has been directed primarily toward extending the technology developed by West Virginia University and others to a large-scale production operation and to the tailoring of wood–polymers to meet specified customer requirements. More than 100 wood types have been processed by Lockheed-Georgia using about a dozen vinyl monomers. Major efforts have been devoted to production of materials using methyl methacrylate, which is considered at this point to be the most attractive monomer overall in spite of its fairly high cost. Lockheed-Georgia products are sold under the trade name Lockwood.

The Radiation Machinery Corporation (Parsippany, N. J.) has begun construction of a radiation facility designed for 5 million curies of ^{60}Co and capable of processing 15 to 20 million sq ft of wood–polymer annually. Production is scheduled to start in 1969. Initial emphasis will be on parquet flooring to be marketed under the trade name Gammite.

In January 1965 AMF (Lowville, N. Y.) built a small pilot plant to make wood–polymer billiard cues by the thermal-catalyst method. AMF's first production unit, consisting of an impregnation chamber 10 in. in diameter and 3 ft long, was built in March 1966. About 70 cue blanks could be prepared at one time. Curing was performed by placing the monomer-impregnated wood cue blanks in a pipe capsule which in turn was placed in a dry kiln. In early 1967 AMF constructed a larger production unit costing about $1000, which can impregnate 150 billiard cue blanks at a time. In the new unit the curing oven is placed alongside the impregnation chamber for minimum handling of the monomer-wet stock. Catalyzed monomer is stored in a refrigerator at 0°C. The time for a complete run, including impregnation and curing, is about 6 hr. This production unit has operated satisfactorily and has consistently produced high-quality cues. AMF estimates production cost at about 20 cents/cue; present production is about 150 cues/day.

Six papers were prepared by U. S. authors for the Bangkok study group. These include an excellent review by Tarkow[8] of the Department of Agriculture's Forest Products Laboratory on the development in the United States of impregnation processes for fibrous materials and an in-depth analysis by Ellwood and Thomas[9] on the structuring of wood and the factors affecting the penetrability of wood by a fluid, i.e., the characteristic permeability of the wood, the nature of the fluid system, and the presence or absence of air in the fluid. Other survey papers covered the degradation of polymers by ultraviolet light,[10] monomer-polymer chemistry and the in situ and graft polymerization processes,[11] impregnation and polymerization meth-

ods and systems used in wood–polymer production,[12] and the status of research, development, and production activities in the United States.[13]

Western Europe

Research relating to the wood–polymer process has been going on in a number of Western European laboratories for several years. Work at various levels of effort has been reported from Austria, Belgium, Denmark, Finland, France, Italy, The Netherlands, Norway, Sweden, the United Kingdom, and West Germany. Recent literature reviews and surveys[14,15] on the status and technology in Western Europe have indicated, however, that except for Denmark, Finland, Sweden, the United Kingdom, and West Germany, the research has been on a very modest scale and in most cases has been only of an exploratory nature. For our purposes here, only the programs expected to have an early impact on the future of wood–polymers will be discussed in any detail.

Austria

The polymerization of methyl methacrylate in spruce has been studied by Gütlbauer and his coworkers[16] at the Reactor Center at Seibersdorf.

Belgium

The only available report on Belgian work relates to the impregnation of spruce and poplar with methyl methacrylate at the Centre d'Études Nucléaires in Mol.[17]

Denmark

Wood–polymer research in Denmark[18,19] is performed at the Risø Research Establishment of the Atomic Energy Commission in cooperation with the Danish Wood Research Laboratory. An important activity has been the preparation and investigation of materials produced from beech, pine, spruce, and birch using methyl methacrylate, vinyl acetate, styrene–acrylonitrile mixtures, and unsaturated polyester–styrene mixtures. From the copolymerization work, it appears that a molar ratio of 60:40 is optimum for the styrene–acrylonitrile system, and from 60:40 to 80:20 for the polyester–styrene system. Properties being studied with the various wood–polymer combinations include dimensional stability, bending strength, hardness, abrasion resistance, and water absorption. Machining and gluing techniques are also being investigated. Samples of paddles, knife handles, gunstocks, and parquet flooring have been prepared and tested.

A unique feature of the Danish work is the experimental comparison of the polymerization reaction in wood using 10-Mev electrons from a 5-kw linear accelerator and photons from a 10-kilocurie ^{60}Co source. The electron irradiations were performed at a dose rate of 5 Mrads/sec and the photon irradiations at a dose rate of 55 rads/sec. Although the polymer yields per unit dose for electron irradiation were only about one-tenth those for photon irradiation, it was generally concluded that electron irradiation might eventually be employed in the processing of fiberboard, wood veneer, and other similar thin materials.

Finland

In recent years the Finnish wood and wood-products industry has been experiencing strong competition from the United States and Canada, and at the same time the competition from new metal products and plastics has been constantly increasing. As a consequence the industry has taken an aggressive interest in the possibilities of upgrading wood and wood products. This was shown by the intense interest in the Scandinavian symposium.

In Finland two organizations have been independently carrying out research on wood–polymers since about 1965. One is the research laboratory of the Neste Oil Refining Company near Porvoo, the other the Department of Radiochemistry of the University of Helsinki.

The Neste Company has concentrated on the use of chemical catalysts for initiation of the polymerization reaction. The Neste process[20] involves the use of a monomer mixture containing as much as 90% styrene. The reaction is started by heating the impregnated material to about 80°C and then maintaining it between 80 and 100°C until the completion of polymerization. Rapid temperature increases are prevented by controlling the rate of polymerization with retardants. Details on the monomer mixture and the catalyst employed have not been published.

The prime mover behind the program at the University of Helsinki is Professor Jorma Miettinen who has conducted experiments on both radiation and chemical curing and has pioneered in the use of mixtures of polyesters and styrene for wood–polymer preparation.[21,22] His monomer impregnation procedure is to (*a*) evacuate to 20 mm Hg and hold for 30 min; (*b*) pressurize to 1 atm nitrogen and hold for 5 min; (*c*) reevacuate to 20 mm Hg and hold for 30 min;

and (*d*) introduce the monomer, pressurize to 1 to 6 atm nitrogen, and hold for 2 to 4 hr. An overpressure is normally used with the polyester–styrene mixtures because of their viscosities.

Polymerization by gamma radiation is effected under a nitrogen atmosphere using a 10-kilocurie ^{60}Co source having a dose rate of about 50 krads/hr at 0.5 m. A 1- to 1.2-Mrad dose is required to polymerize methyl methacrylate, whereas 0.9 to 1.1 Mrads is needed to polymerize a polyester–styrene mixture having a ratio of about 1:1. Mixtures containing more polyester are more easily polymerized; less than 0.5% styrene usually remains unpolymerized. Chemical-catalyst experiments have involved polyester–styrene and benzoyl peroxide (0.5 to 1%); curing has been for 24 hr at about 60°C. Results are essentially the same as for radiation curing when the same wood and monomer mixtures are used.

In the work at the University of Helsinki as well as at Neste, the emphasis has been on birch and alder because they are easily impregnated and do not contain polymerization inhibitors. Fir, pine, and aspen have been found to impregnate unevenly. When polymerized under pressure (6 to 9 atm), alder gives a wood–polymer containing 55 to 60% polymer, aspen about 55%, and birch and pine about 45%.

The University of Helsinki, working with the Wood Technology Laboratory of the Finnish State Institute for Technical Research, has performed two studies on strength and stability.[22-24] The first was with birch impregnated with 10 different commercial polyester—styrene mixtures and methyl methacrylate. The results indicated that the type of polymer did not have much effect on the strength of the resulting wood–polymer and that an insufficient number of test pieces had been used for statistically significant results. Accordingly, an expanded program was instituted using four wood species (birch, alder, aspen, and pine) impregnated with the best of the polyester–styrene mixtures from the first study. This mixture was prepared by adding 33% styrene to Soredur H 75 (Svenska Oljeslageri Ab, Mölndal, Sweden) to give a final styrene content of 55%. The birch and alder were also impregnated with methyl methacrylate. A total of some 27,000 samples was prepared, of which 6300 were impregnated and 6000 selected for testing. The greatest improvements were in hardness (5 to 9 times the control), abrasion resistance (2 to 9 times the control), and dimensional stability. Alder, a cheap and relatively weak species, gave a wood–polymer having a durability as good as that of birch. In general, differences in the physical properties of the polyester–styrene- and the methyl methacrylate-based materials were small. Complete details of these studies will soon be published in the Proceedings of the Finnish State Institute of Technology.

A processing method[25] developed by the Wilh. Schauman Company, which has been applied to plywood, chipboard, sawed goods, and paper, involves impregnation with a polyester–styrene mixture at low pressure followed by polymerization in a hot press over a time period of from 1 to 5 min. After impregnation, excess polymer is shaved away from the edges. All boards investigated showed smooth surfaces of quality corresponding to that of the press platens. A pilot model of an impregnator for industrial-scaled production has been tested. Also at the Wilh. Schauman Company, experiments have been performed on the improvement of chipboard by impregnating with a monomer and polymerizing by means of radiation and catalysts.[26]

In an attempt to determine the relative costs of producing wood–polymers and other polymer-containing fibrous materials, Rotkirch[27,28] performed a cost analysis covering both catalytic and radiation curing. He concluded that, for a production rate of 10,000 m^2/hr in a plant operating 8000 hr/year, it is more economical to manufacture ½-in. fiberboard by radiation curing than by catalytic curing. A similar situation would exist for the production of 20-mm-thick bagasse board. He indicated that this is due mainly to the more expensive monomer mixture necessary in the catalytic case. He and others have speculated that difficulties involved in storing monomers already charged with catalysts might add significantly to costs, particularly in the large production plant.

Four tests are currently under way to evaluate wood–polymer materials in Finland: in a school in Helsinki, parquet floors of birch–polyester–styrene, oak–methyl methacrylate, and untreated heavily lacquered oak are being compared under heavy use; window frames of wood–polymer are being evaluated for use in saunas; skis covered underneath with a thin veneer of wood–polymer are being compared with regular skis under cross-country conditions; and a group of lacquered and unlacquered wood–polymer samples with controls is being exposed to natural weather conditions on a roof in Helsinki.

France

There has been no information published on wood–polymer research in France since the Euratom

symposium in Brussels in October 1966 (Refs. 29 and 30). It has been reported, however, that, in cooperation with the Japan Atomic Energy Research Institute, a program is under way at the Centre d'Études Nucléaires, Saclay.[31]

The Netherlands

Griffioen[32] has studied the polymerization of methyl methacrylate in spruce, beech, and pine by chemical catalysts and has determined selected properties of the resulting wood–polymers.

Norway

It was reported at the Scandinavian symposium that wood–polymer research has been initiated at the Atomic Energy Institute at Kjeller and the Central Institute for Industrial Research in Oslo.

Sweden

The first comprehensive report[33] on wood–polymer studies in Sweden became available in early 1967. This report covers research on the radiation-induced polymerization of methyl methacrylate, butyl methacrylate, styrene, and acrylonitrile in pine, spruce, birch, and beech performed during the period July 1, 1964, to Dec. 31, 1966, at the Swedish Research Council's Laboratory and the Section of Nuclear Chemistry, AB Atomenergi. Specific studies were aimed at obtaining a better understanding of the impregnation and polymerization processes including the doses required for complete polymerization, the effects of different solvents on the rate and extent of polymerization, the effect of the water content of the wood on impregnation efficiency, and the molecular weight and distribution of the polymers formed. An effort was also directed at determining the physical and mechanical properties of the wood–polymer materials produced. Results were reviewed in some detail in papers presented at the Bangkok study group[15] and the Scandinavian symposium.[34,35]

At the Bangkok meeting, Kinell[15] and Gotoda[75] reported on an attempt to produce by radiation emulsion-polymerization wood–polymers having a high degree of grafting. Two monomers, methyl methacrylate and styrene, were used in 50 to 70 wt.% water emulsions with four species of wood and with a variety of emulsifying agents. Although the expected 100% conversion was not realized (no more than 60% of the monomer was polymerized in any of the combinations tried), about half of the polymer formed was grafted.

Current interest in the use of wood–polymer materials in Sweden is directed largely to flooring and window construction. The cost of producing wood–polymers for these applications is estimated, however, to be between 2.3 and 3,5 times the cost of producing a polyglycol-impregnated wood having many comparable properties.[36] At the present time, there is no effort directed toward the production of wood–polymers on a large scale. (A marketing study of wood–polymer products has been made;[37] however, it has not been reviewed by the authors of this paper.) In fact, small-scale production of standard samples sufficient for a more thorough evaluation of physical and mechanical properties has been delayed because a suitable radiation source has not been available. Collaboration with industrial companies has led to the preparation of samples of spacers for fuel cells, parquet flooring, rollers for the spinning industry (tested but found too hard), knife handles, folding pocket rulers, and veneer for fiberboard.

It is generally recognized by the researchers in Sweden that, if there is to be a viable wood–polymer industry, the initiative must, in large measure, come from people concerned with wood and wood products. The usual procedure, in which the nuclear scientists and the radioisotope-applications engineers determine the course of events as a part of a program to find peaceful uses for nuclear energy, is not expected to lead to any significant commercialization. And notwithstanding the technical advances to date, if commercialization is to be achieved, it will probably be necessary to (*a*) find cheaper monomers; (*b*) develop means of incorporating the monomers in the wood so that a smaller amount of polymer (monomer used) will give a greater reinforcement of structure; (*c*) develop methods for using wood all of a given species rather than only that which has been carefully selected; and (*d*) develop facilities suitable for impregnating and irradiating sheets and boards in large quantities.

United Kingdom

Work at the Forest Products Research Laboratory, first reported in 1966 (Ref. 38), has led to the production and commercial utilization of at least one wood–polymer product in the United Kingdom, i.e., handles for table cutlery. The handles are reported to be of styrene–acrylonitrile-impregnated sycamore irradiated to a dose of 1.5 Mrads, the irradiations being performed in the ^{60}Co facility at the United Kingdom Atomic Energy Authority's Wantage Research Laboratory.

A very interesting study reported by Dalton and McCann[39,40] at both the Bangkok study group and the Scandinavian symposium relates to the use of electron accelerators for the in situ polymerization of monomers in fibrous materials. In particular, Dalton and McCann treated in some detail the electron processing of fiberboard up to 1 in. in thickness and to 4 ft in width. Some of their observations and conclusions are as follows:

1. Taking into consideration window and air-gap losses and assuming a surface-to-surface dose ratio of 2:1, the electron energy required for processing monomer-impregnated fiberboard from one side would be 1.0 to 1.3 Mev for $\frac{1}{8}$-in.-thick board and 6.1 to 9.1 Mev for 1-in.-thick board. For irradiation from both sides, the electron-energy requirement (assuming a 2:1 surface-to-interior dose ratio) would be reduced to 0.5 to 0.6 Mev for $\frac{1}{8}$-in.-thick board and to 4.0 to 5.2 Mev for 1-in.-thick board.

2. The upper limit on particle energy for a commercially viable installation would be about 5 Mev, necessitating double-sided irradiation for all boards thicker than about $\frac{3}{8}$ in.

3. The power required to deliver a dose of 5 Mrads to $\frac{1}{8}$-in.-thick, 4-ft-wide board would be 7.1 to 9.0 kw per 1000 sq ft/hr for single-sided irradiation and 3.3 to 4.1 kw per 1000 sq ft/hr for double-sided irradiation. For $\frac{3}{8}$-in.-thick board, the power for single-sided and double-sided irradiation would be 20 to 26 and 9.1 to 12.8 kw per 1000 sq ft/hr, respectively.

4. For a plant treating 10,000 sq ft/hr of $\frac{1}{8}$-in.-thick, 4-ft-wide board to 5 Mrads, the overall cost of the radiation based on a 5-year amortization and 10% interest on capital would be about 0.2 cent/sq ft for a 5000-hr operating year, 0.3 cent/sq ft for a 2000-hr year. For $\frac{3}{8}$-in.-thick board, the costs would be, respectively, 0.3 and 0.5 cent/sq ft. In the latter case the accelerator capital cost would be about $300,000; in the former about $170,000.

5. The treatment of 1-in.-thick boards at throughputs of 10,000 sq ft/hr and above is not economically feasible with existing equipment.

6. The optimum approach to fiberboard treatment may be to use electrons accelerated to energies at which they do not penetrate more than 1 to 2 mm. The board riding on a continuous conveyor would be coated with monomer just before reaching the electron beam so that the monomer would have time to penetrate only to the prechosen depth before being cured. Not only would this be cheaper than treating full thickness but also the excellent acoustic and thermal-insulation properties of untreated fiberboard would be retained.

West Germany

Burmester[41] was one of the first, along with Miettinen in Helsinki and Czvikovszky in Budapest, to experiment with polyester–styrene mixtures. Burmester's results may be questionable, however, because the radiation doses selected for study (0.001, 0.1, and 10 Mrads) were far from ideal. (According to Czvikovszky[42] and Miettinen,[22] an optimum dose for polyester–styrene systems is about 1 Mrad.) Burmester's interest in the irradiation of wood systems extends back for several years and includes studies on the effect of radiation on wood and wood-base materials[43,44] and the treatment of woods with monomers in the vapor phase.[45]

Some other interesting West German work is by Orth,[46,47] who has studied the properties of chipboard impregnated with methyl methacrylate and polymerized by chemical means. The bending strength, modulus of elasticity, and surface hardness of the treated board were found to increase threefold and the tensile strength tenfold. The comment by Czvikovszky and Dobo[42] that it would be more efficacious to combine polymer and chips at the time the board was produced has been checked, but not substantiated, by Miettinen[48] in preliminary experiments using polyester as the binding agent. It is Miettinen's feeling that when chipboard, produced in the usual manner with urea resin as the binding agent, is impregnated with a monomer that is polymerized in situ, the formation of the second three-dimensional polymer network within the cavities of the original network should indeed give rise to a chipboard having improved properties compared to ordinary chipboard.

Eastern and Central Europe

Excellent accounts of the research being conducted in Eastern and Central Europe were presented by Czvikovszky and Dobo at the Bangkok meeting[42] and by Czvikovszky alone at the Scandinavian symposium.[49] Both authors are scientists at the Research Institute for Plastics in Budapest, Hungary.

Czechoslovakia

Research into wood–polymer and allied problems such as grafting to paper and other cellulose material

was reported to be in progress in at least two institutes. Pesek[50] (Isotopes Institute, Pardubice) has studied vapor-phase grafting using the preirradiation and the peroxide techniques, and Varga[51,52] (University of Bratislava) has studied the poplar–styrene radiation polymerization system using various solvents and swelling agents, including methanol, dioxane, and water.

Hungary

Extensive research on radiation-initiated wood–polymer combinations has been performed by Czvikovszky and his coworkers.[53-55] In particular, the use of comonomer and monomer–polyester oligomers has been stressed. An overpressure of about 1.5 atm was used for vinyl chloride–vinyl acetate monomer combinations. The polyester–vinyl monomer combinations gave up to a 50% increase in bending strength for Hungarian beech; there is a possible interest in this material for use in textile shuttles.

Another study of great interest undertaken by Hungarian researchers compared chemical catalyst alone, radiation alone, and chemical catalyst plus radiation for initiation. Styrene–acrylonitrile and polyester–styrene mixtures in beech and hornbeam wood were used. In general, it was shown that good conversions could be obtained with benzoyl peroxide at 60°C; for example, with 1.5% catalyst, 20% polymerization was reached in 17 hr. The problem was that a further temperature rise of 30 to 40°C took place in the center of the samples and part of the resin ran or was sweated out. With radiation, on the other hand, samples appeared to cure evenly and temperature rises of only 5 to 10°C were observed, although reasonably large doses were required for complete conversion of monomer to polymer. In the case of 50:50 styrene–acrylonitrile mixtures, for example, 1.4 Mrads led to only 18% polymerization. However, a combination of 1.5% benzoyl peroxide and a dose of 0.21 Mrad delivered in 2.1 hr gave 24% polymerization with only minor temperature increases. It might well be that a combination of radiation and chemical initiation will be the final solution of the radiation versus chemical initiation controversy.

USSR

Work on wood–polymers has been under way in the Soviet Union for many years, the first publications being patents[56] in 1958 and 1960 and an article in the American technical literature[57] in 1960. Since that time there has been comparatively little research work published by Russian scientists, and efforts appear to have been concentrated in pilot-plant studies with a view toward industrial development. A 0.5-ton/day pilot plant has been constructed in the Karpov Institute in Moscow. Wood samples up to 4 in. thick have been used; greater thicknesses were found to give problems due to the exotherm associated with the polymerization, raising the temperature by 50°C in some cases. Boards up to 20 by 40 in. have been processed. Cobalt-60 irradiation with dose rates of about 100,000 rads/hr leads to a processing time of about 10 hr. The actual irradiations are performed in 15- to 100-liter containers in which the wood is placed, the containers are evacuated, and distilled monomer is added at room temperature. After soaking, the excess monomer is blown out with nitrogen gas and the containers are irradiated. A large variety of woods and monomers has been studied. Apparently, a parquet floor of wood–polymer is permanently exhibited in the Atomic Energy Pavilion in Moscow.

A few papers published in 1961–1967 (Refs. 58 to 62) cover work with new monomers and other reagents; included is the vapor-phase grafting and plasticization of wood with gaseous or liquid ammonia.

Asia

No general review of the work being performed on wood–polymer combinations in Asia has been published. However, at the Bangkok study group a number of reports were presented by representatives of the various participating Asian countries.

India

Most of the research and development in wood–polymer combinations in India is being conducted by the Isotope Division of the Bhabha Atomic Research Center. The status and results of this work are given in an excellent paper by Iya.[63] The effort is presently concentrated on the lighter, cheaper, and less durable species of Indian woods with styrene as the monomer, methyl methacrylate and vinyl acetate having been considered in earlier studies. A considerable number of plasticizers, solvents, and catalysts have been evaluated in conjunction with styrene. For radiation polymerization studies, samples were sealed in polyethylene wrappers, and for thermocatalytic studies, in Pyrex tubes. It was found that the addition of plasticizers decreased the radiation dose required for complete polymerization. In the case of the heat–catalyst

method, there did not appear to be any advantage in the use of plasticizers. With radiation, the addition of a heating step prior to the irradiation led to a marked decrease in the dose needed. Thus 24 hr of heating at 90 to 100°C reduced the polymerization dose for styrene in pine wood from 9.2 Mrads to 3.6 Mrads. In the same system, 20% of diisooctyl phthalate plasticizer added to the styrene reduced the dose from 6.4 Mrads to 2.1 Mrads. Another method of reducing the total dose was to impregnate the wood with partially polymerized styrene in carbon tetrachloride solutions.

The methods of impregnation studied included both the evacuation technique and the use of higher pressures for the more viscous impregnates and less porous types of wood. Benzoyl peroxide was the main chemical catalyst used. With regard to the straight radiation experiments, it was found that the total dose needed was lower at lower dose rates, as observed by many previous workers. In general, the physical properties of all the treated woods improved as compared to the untreated woods, and particularly good results were obtained with the lighter woods. There seemed to be a tendency toward better results for the materials containing plasticized styrene, but the results were not conclusive, and further studies are in progress.

With styrene, the heat-plus-radiation treatment gave good improvements in physical properties. For example, in pine wood (*Pinus longifolia*) at a polymer loading of about 30%, 12 hr of heating before irradiation gave a 42% improvement in compression strength compared with a 13% improvement for radiation alone. The impregnation with partially polymerized styrene in carbon tetrachloride plus radiation gave 43% strength improvement. The heat-plus-radiation method appears particularly promising, and a rather extensive program of research into this and other methods with a number of woods and with bamboos is presently under way.

Japan

An interesting and rather detailed report on the present status of research in Japan on wood–polymer combinations was prepared by Hirayama of the Showa Denka Corporation.[31] An extensive series of researches has been conducted at the Government Forestry Institute near Tokyo by Murayama and his colleagues since 1961 (Refs. 31 and 64). Murayama has given the name Plamowood to his products. Chemical and radiation initiation and a combination of both have been studied. Both ^{60}Co and a 2-Mev Van de Graaff electron accelerator have been used as radiation sources. Many different species of wood and kinds of chipboard and fiberboard have been investigated. Basic studies have been concerned with wood structure and have included electron-spin-resonance studies of the radical concentration in irradiated woods. Differences between grafted and in situ polymerized products and the effect of solvent type and concentration have all been investigated in detail. The present method of producing wood–polymer specimens involves evacuating the wood to 2 mm Hg for 6 hr, after which the monomers are allowed to diffuse into the wood. Polymerization is initiated either by irradiation in air or under vacuum at room or high temperature or by chemical catalyst and heat. Chemical initiation seems to be best for smaller specimens and radiation or a combination of radiation plus chemical catalyst for larger pieces. A 50:50 mixture of styrene and methyl methacrylate has been found to represent a good compromise among cost, dose required to polymerize, and physical properties. Among the properties studied in detail have been water sorption and the antishrink efficiency of the wood–polymers prepared under a wide variety of conditions. These properties are particularly important in Japan because of the large seasonal changes in humidity. In addition, a number of experiments have been conducted to impart flame retardance to wood. These include the treatment with fire-retarding monomers alone, with monomers containing a separate flame retarder such as halogenated organic phosphates, and with conventional commercial flame retarders prior to monomer impregnation and polymerization. Other Japanese researchers have studied the polymerization of methyl methacrylate, styrene, and other monomers in wood using a variety of chemical initiations as well as radiation. The hardness of most woods was found to increase considerably with the polymerization treatment. In addition, the shearing and compression strengths and the abrasion resistance all improved. One other feature specifically mentioned was the development of a glossy finish upon buffing the wood–polymer combinations. Among the applications under study in Japan are railroad ties, paneling, sporting goods, parquet flooring, and furniture. Dimensional stability is considered to be the common indispensable property in all uses.[65]

A joint Japanese–French research program on wood–polymers has been undertaken by the French Atomic Energy Commission. The methods of fabrication and density studies will be emphasized in the French research and the means of improving the

dimensional stability and flame retardancy in the Japanese studies.

Korea

There is no wood–polymer research program in Korea at the present time, although plans are being made for work to be initiated.

Pakistan

Although Pakistan was not represented at the Bangkok meeting, two papers[66,67] were subsequently submitted for the Proceedings. The single effort in Pakistan has been directed toward modifying the qualities of jute fiber. The radiation grafting of styrene, methyl methacrylate, and acrylonitrile to the jute and its effect on water repellency, resistance to attack by microorganisms, and breaking load (of jute yarn) have been studied. Results show an improvement in water repellency and resistance to attack by microorganisms but a deterioration in strength. Interestingly, radiation grafting was found to reduce the breaking load much more severely than radiation alone.

Philippines

A program of research into wood–polymer materials was initiated at the Philippine Atomic Research Center in late 1966 (Ref. 68). A highly porous, fast-growing wood (*Anthocephalus cadamba*) was chosen for the study. Methyl methacrylate and hydroxypropyl methacrylate were used as monomers. The wood specimens were placed in aluminum cylinders, pumped out for 30 min, and then immersed in monomer overnight. Excess monomer was drained off, and the wood was wrapped in plastic film and returned to the cylinder, which was then flushed with nitrogen and irradiated with ^{60}Co gammas. The wood–polymer samples were much harder than the original wood and were machined to give an excellent satin finish with enhanced grain structure. In addition, the static-bending and compression strengths increased by 33 and 140%, respectively, over the untreated wood. The results of this initial work were encouraging, and the research is being continued. As in Taiwan, there is considerable interest in the Philippines in developing wood carvings from abundant softwood species stabilized and strengthened by the wood–polymer process.

In addition to the wood–polymer studies, radiation grafting of various monomers to kenaf and other fibers produced in the Philippines is being investigated, but no results are yet available.

Taiwan

The work reported for Taiwan was performed almost entirely at the Union Industrial Research Institute.[69,70] Attention was centered on plywood, wood-particle board, wood fiberboard, bagasse board, and bamboo. The method used was to evacuate the vessel containing the material to be impregnated to 10 mm Hg, pressurize the vessel to about 1 atm nitrogen, and again evacuate. A vinyl monomer was then added and allowed to soak into the material under pressure in a nitrogen atmosphere.

In the case of bamboo, the first nitrogen step was omitted because no advantage was found. When vinyl acetate monomers were used, 2 to 3 kg/cm^2 excess nitrogen pressure was used for the impregnation procedure. The water content of the materials was limited to 15% or below and to 5% in the case of bagasse board. Higher water contents seemed to lead to uneven distribution of polymer in the product. The saturated substrates were wrapped in polyethylene film and rotated during exposure to ^{60}Co radiation.

Styrene, methyl methacrylate, vinyl acetate, and vinyl chloride were investigated as monomers. Vinyl chloride polymerizes alone as a powder and was not effective; however, when mixed with 20% vinyl acetate, excellent results were obtained. Although methyl methacrylate gave the best overall property improvements, it was considered too expensive. The vinyl chloride–vinyl acetate mixture (80:20) was regarded as the best compromise between performance and cost. The main beneficial effects of the radiation polymerization treatment for both the wood and bagasse board were (*a*) a more uniform density, (*b*) an increase in hardness, up to 8 times the untreated values, (*c*) an increase in tensile strength, up to 3.5 times the untreated values, (*d*) a reduction in the rate of water absorption, and (*e*) an improvement in the resistance of the product to weathering and insect damage. Applications of polymer-containing wood, bamboo, and bagasse board are being actively studied—particularly for building boards, furniture, and wood carvings.

Thailand

Only a few preliminary experiments had been conducted at the time of the Bangkok meeting.[71] These had resulted mainly in plastic coatings rather than wood–polymers, presumably owing to inadequate penetration of the wood by the monomer. However, an active program on combining polymers with wood species indigenous to Thailand is now under way at the Atoms-for-Peace Center in Bangkok.

Fibrous Material Resources in Asia and the Far East

During the Bangkok meeting, Stacey[72] of the United Nations' Food and Agriculture Organization's Regional Office in Bangkok gave a most informative and helpful review of the actual and potential wood and fiber resources of each country in the Far East. The need in most Far Eastern countries for a low-cost construction board for housing was emphasized. The severe weathering and other environmental conditions in many Asian and other Far Eastern countries lead to a need for upgrading presently available board materials. It is possible that the type of fiber–polymer combination discussed at the study group will eventually help to provide that need.

Australia

Little research appears to have been carried out with wood–polymer combinations in Australia, although there is in progress at the University of New South Wales by Garnett and his coworkers[73] an extensive effort on the radiation grafting of vinyl monomers to cotton and other cellulosic fibers. A comprehensive review of the prospects for a wood–polymer industry in Australia was prepared by Clouston[74] of the Australian Atomic Energy Commission for the Bangkok study group. He concluded that, notwithstanding the excellent irradiation facilities available, the small size of the market and the cost of the monomers required might severely handicap the development of a major industrial effort in Australia.

Summary and Conclusions

The possibilities inherent in the combining of synthetic polymers with wood and other fibrous substrates have attracted the attention of scientists and technologists around the world. Active or projected programs in this field exist in at least 25 countries. Although some work has been carried out by the direct sorption of polymers into wood, almost all the work involves impregnating the fibrous substrate with a monomeric material and polymerizing in situ. In general, no special attempts are made to promote actual grafting as opposed to in situ homopolymerization. Although chemical initiation is under active study, radiation appears to be the main means of initiation and is presently the preferred method. There is, however, growing interest in combining chemical catalysts and radiation to promote the polymerization process. In many Far Eastern countries, there is a desperate need for a cheap building-board material which will stand up to the attack of insects, microorganisms, and severe weather conditions. There is hope that polymer–fiber board and similar combinations might help to fill this need. (PSB)

References

1. S. L. Ross and J. W. Hodgins, Irradiated Wood–Polymer Combinations, *Isotop. Radiat. Technol.*, 3(3): 236-244 (Spring 1966).
2. A. G. Davies and C. G. Smith, The Physical Properties of Wood–Plastic Combinations Made from Canadian Woods, paper presented at Meeting of Forest Products Research Society, Eastern Ontario Section, Toronto, Canada, April 1968.
3. A. G. Davies, B. H. Asbury, and C. G. Smith, Radiation Polymerization Kinetics in Wood–Polymer Preparation, paper presented at 22nd Annual Meeting of Forest Products Research Society, Washington, D. C., June 1968.
4. A. G. Davies, The Kinetics of Gamma-Radiation-Induced Polymerization in Wood–Polymer Preparation: A Thermometric Method for the Determination of Reaction Rates, Paper No. 4, Session No. 2, in *Proceedings of Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20-21, 1968, Radiokemiska Institutionen vid Helsingfors Universitet, 1968.
5. A. J. Felice, Radiation Engineering in the Polymerization of Monomers in Fibrous Materials: Radioisotopes Source, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 71-82, IAEA, Vienna, 1968.
6. W. R. Boyle and A. W. Winston, Preparation of Wood–Polymer Combinations Using Gamma Radiation To Induce Polymerization, Final Report of USAEC Contract No. AT(40-1)-2945 (to be published March 1969).
7. W. K. Poole, An Investigation of Certain Physical and Mechanical Properties of Wood–Polymer Combinations, Final Report of USAEC Contract No. AT(40-1)-2513 (to be published March 1969).
8. H. Tarkow, History of Impregnation Techniques with Fibrous Materials, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 3-16, IAEA, Vienna, 1968.
9. E. L. Ellwood and R. J. Thomas, The Permeability of Wood in Relation to Its Structure and Penetrability by Fluids, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 19-33, IAEA, Vienna, 1968.
10. D. T. Turner, Degradation of Polymers by Ultraviolet Light, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 93-105, IAEA, Vienna, 1968.
11. V. T. Stannett, Monomer–Polymer Chemistry and the Impregnation Process, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 45-55, IAEA, Vienna, 1968.
12. W. E. Mott and G. J. Rotariu, Impregnation and Polymerization Methods and Systems Used in the Production of

Wood–Polymer Materials, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 83-91, IAEA, Vienna, 1968.

13. G. J. Rotariu and W. E. Mott, Status and Technology of Polymer-Containing Fibrous Materials in the United States, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 190-208, IAEA, Vienna, 1968.
14. A. Burmester, European Research Work on Polymer Wood, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 209-216, IAEA, Vienna, 1968.
15. P. O. Kinell and P. Aagaard, Status and Technology of Polymer-Containing Fibrous Materials in Western Europe with Special Reference to Sweden, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 129-151, IAEA, Vienna, 1968.
16. F. Gütlbauer, E. Proksch, and H. Bildstein, Radiation-Hardened Wood–Plastic Combinations, *Oesterr. Chem.-Ztg.*, **67**: 349-360 (1966).
17. M. DeProost, H. Hoeyberghs, and W. Schietecatte, Belgian Research on the Use of Radiation Technology for the Preparation of Wood–Plastic Combinations, *Eurisotop Arbeitsunterlage No. 45*, Brussels (1966).
18. K. A. J. Singer, Wood–Plastic Combinations Prepared by Irradiation with Gamma Rays and High-Energy Electrons, in *Proceedings Second Tihany Symposium on Radiation Chemistry*, pp. 715-726 (1967), Publishing House of the Hungarian Academy of Sciences, Budapest, 1967.
19. K. A. J. Singer, Th. Thomassen, and A. Vinther, Impregnation of Wood with Plastic Materials: Status of Research in Denmark (in Swedish) Paper No. 2, Session No. 4, in *Proceedings of Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20–21, 1968, Radiokemiska Institutionen vid Helsingfors Universitet, 1968.
20. V. Tamella, Finnish Patent Application No. 3416/66; *Kem. Teollisuus*, **24**: 183 (1967).
21. J. K. Miettinen, Present Status of Research on Wood–Plastic Combinations, in *Application of Radioisotopes in the Pulp and Paper Industry*, Report of a Panel, Helsinki, Finland, October 1967, pp. 91-102, International Atomic Energy Agency, Vienna, 1968.
22. J. K. Miettinen, Status and Technology of Impregnated Fibrous Materials in Finland, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 152-168, IAEA, Vienna, 1968.
23. J. K. Miettinen and T. Autio, Tests on Physical Strength of Wood–Plastic Combinates, paper presented before IAEA Panel on the Application of Radioisotopes in the Pulp and Paper Industry, Helsinki, Finland, October 1967.
24. F. E. Siimes, Physical and Strength Tests on Finnish Wood–Polymer Material (in Swedish) Paper No. 2, Session No. 5, in *Proceedings of Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20–21, 1968, Radiokemiska Institutionen vid Helsingfors Universitet, 1968.
25. A. Mäkinen, Surface Impregnation of Construction Sheets: Results of Some Application Tests (in Swedish) Paper No. 2, Session No. 7, in *Proceedings of Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20–21, 1968, Radiokemiska Institutionen vid Helsingfors Universitet, 1968.
26. P. Nykanen, Possibility of Increased Sales of Chipboard by Improving the Quality (in Swedish), Paper No. 4, Session No. 1, in *Proceedings of Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20–21, 1968, Radiokemiska Institutionen vid Helsingfors Universitet, 1968.
27. E. Rotkirch, Production Economics of Impregnated Fibrous Materials, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 327-347, IAEA, Vienna, 1968.
28. E. Rotkirch, Production Economy of Impregnated Fibrous Materials, Paper No. 1, Session No. 8, in *Proceedings of Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20–21, 1968; Impregnation of Fibrous Materials—Economy of Various Curing Methods, *Särtryck ur Papper och Trä*, No. 4: 1 (1968).
29. J. Feuillet, Technological Characteristics of Wood–Plastic Combinations, *Eurisotop Arbeitsunterlage No. 45*, Brussels (1966).
30. J. R. Puig and J. Laizier, Importance of Grafting with Respect to the Filling Up of Voids in Wood–Plastic Combinations, *Eurisotop Arbeitsunterlage No. 45*, Brussels (1966).
31. T. Hirayama, Status and Technology for Wood–Plastic Composites in Japan, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 250-261, IAEA, Vienna, 1968.
32. K. Griffioen, Properties of Wood–Plastic Combinations, *Eurisotop Arbeitsunterlage No. 45*, Brussels (1966).
33. P. O. Kinell and P. Aagaard, A Study of Wood–Polymer Combinations, Forskningsrådens Laboratorium (Studsvik), Swedish Report LFK-9, March 1967.
34. P. Aagaard and L. Eriksson, Strength and Dimensional Stability of Swedish Wood–Polymer Materials (in Swedish), Paper No. 1, Session No. 5, in *Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20–21, 1968, Radiokemiska Institutionen vid Helsingfors Universitet, 1968.
35. P. O. Kinell and P. Aagaard, Impregnation and Polymerization of Monomers in Wood, Paper No. 1, Session No. 4, in *Proceedings of Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20–21, 1968, Radiokemiska Institutionen vid Helsingfors Universitet, 1968.
36. R. Morén, Marketing Aspects of Plastic-Impregnated Wood Products (in Swedish), Paper No. 2, Session No. 8, in *Proceedings of Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20–21, 1968, Radiokemiska Institutionen vid Helsingfors Universitet, 1968.
37. G. Carleson, Market for and Economics of Wood–Polymer Products in Sweden, *Svensk Kemisk Tidskrift*, 79(10): 549 (1967).
38. E. J. Gibson, R. A. Laidlaw, and G. A. Smith, Dimensional Stabilisation of Wood, *J. Appl. Chem.*, **16**: 58-64 (1966).
39. F. L. Dalton and J. D. McCann, Radiation Engineering in

the Polymerization of Monomers in Fibrous Materials: Accelerators, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 57-70, IAEA, Vienna, 1968.

40. F. L. Dalton and J. D. McCann, The Use of Electron Accelerators in the Curing of Impregnated Fibrous Materials, Paper No. 3, Session No. 6, in *Proceedings of Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20–21, 1968, Radiokemiska Institutionen vid Helsingfors Universitet, 1968.
41. A. Burmester, Experiments on the Improvement of Wood by Radiation-Polymerized Plastic Monomers, *Holz Roh-Werkstoff*, 25:(1): 11 (1967).
42. T. Czvikovszky and J. Dobo, The Status of Wood–Plastic Combination Research in Europe, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 169-189, IAEA, Vienna, 1968.
43. G. Becker and A. Burmester, Change of Wood Properties Caused by Gamma Irradiation, *Materialprüfung*, 4: 416-426 (1962).
44. A. Burmester, Effect of Gamma Rays on the Chemical, Morphological, Physical, and Mechanical Properties of Pine and Beech Wood, *Materialprüfung*, 8: 205-211 (1966).
45. A. Burmester, Investigation of the Treatment of Wood with Formaldehyde Monomer by Use of Gamma Rays, *Holzforschung*, 21(1): 13 (1967).
46. H. Orth, R. Ammon, W. Burkard, H. Conzelmann, and J. Schulze, New Tests with Wood–Plastic Combinations, *Holz-Zentralblatt*, 92(148): 2592 (1966).
47. H. Orth, Wood–Plastic Combinations, *Gummi-Asbest-Kunststoffe*, 6: 666 (1967).
48. J. K. Miettinen, The Impregnation of Fibrous Materials with Plastics: Current Research and Technology, *Särtryck ur Papper och Trä*, No. 2 (1968). (Available in English Translation from the IAEA as PL-276.)
49. T. Czvikovszky, Wood–Plastic Combination Research in Eastern and Central Europe, Paper No. 1, Session No. 6, in *Proceedings of Scandinavian Symposium on Applications of Plastics in the Wood Processing Industry*, Helsinki, Finland, May 20–21, 1968, Radiokemiska Institutionen vid Helsingfors Universitet, 1968.
50. M. Pesek and J. Jarkovsky, Irradiation Grafting of Cellulose by Methyl Methacrylate in Vapour Phase by Preirradiation Technique (in Czech), *Chem. Prumysl*, 17: 42/9, 482 (1967).
51. S. Varga, M. Kosik, and S. Katuscak, Modification of Wood by Radiation. I. The Improved Poplar–Styrene System, *Jad. Energ.*, 13(6): 220 (1967).
52. S. Varga and M. Kosik, Radiation Chemical Effects in Wood–Vinyl Monomer Systems (in Czech), *Jad. Energ.*, 13(2): 62-69 (1967).
53. T. Czvikovszky and G. Kolosvary, Wood–Plastic Combinations by Radiation Chemical Way (in Hungarian), *Faipar*, 17(6): 164 (1967).
54. T. Czvikovszky, Wood–Plastic Combination by Monomer Impregnation and Radiation Polymerization, Report of the Plastics Research Institute, Budapest, No. 8, 1967. Also in *At. Energy Rev.*, 6(3): 3-99 (1968) (166 references).
55. T. Czvikovszky and G. Kolosvary, Improving of Wood by Radiation-Induced High Polymers, *Plaste Kaut.*, 14(9): 623 (1967).
56. A. S. Freidin, Yu. M. Malinsky, V. L. Karpov, and N. T. Romanov, Russian Patents SSSR 122 219 (1958) and 126 562 (1960).
57. V. L. Karpov, Yu. M. Malinsky, V. I. Serenkov, R. S. Klimanova, and A. S. Freĭdin, Radiation Makes Better Woods and Copolymers, *Nucleonics*, 18(3): 88-90 (1960).
58. T. J. Krasovitskaya, Modification of Wood by Polymerization of Impregnating Monomers by Gamma Radiation, in *Transactions of the Second All-Union Conference on Radiation Chemistry*, 1960, p. 511, Izd. AN SSSR, Moscow, 1962.
59. A. S. Freĭdin, Yu. M. Malinsky, and V. L. Karpov, Effects of Ionizing Radiations on the Properties of Wood and Its Components, in *Proceedings of the Tashkent Conference on the Peaceful Use of Atomic Energy*, Tashkent, 1959, Vol. I, pp. 538-546, Publishing House of the Academy of Sciences, Uzbek SSR, 1961.
60. A. J. Kalnin'sh, Plastification of Woods, *Izv. Akad. Nauk Latv. SSR*, 4(201): 48 (1964).
61. A. J. Kalnin'sh, Kreitsberga, and V. N. Sergeeva, The Effect of Ionizing Radiation on Chemically Treated Wood, *Latv. PSR Zinat. Akad. Vestis, Kim. Ser.*, 6: 714 (1966).
62. A. J. Kalnin'sh, Physical and Mechanical Properties of Wood Chemically Plastified by Use of Ammonia, *Holztechnologie*, 8(1): 23 (1967).
63. V. K. Iya, Status of Technology of Polymer Containing Fibrous Materials in the Eastern Hemisphere: India, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 231-249, IAEA, Vienna, 1968.
64. T. Murayama, Studies on Radiation Treatment of Wood and Wood Substances: Radiation Grafting of Vinyl Comonomers to Wood, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 262-263, IAEA, Vienna, 1968.
65. T. Hirayama, Potential Markets for Wood Plastic Composites in Japan, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 349-364, IAEA, Vienna, 1968.
66. M. H. Awan and A. Husain, Modification of Qualities of Jute-Fibre: Graft-Copolymerization Under Irradiation and Its Effect on Water Repellency and Resistance to Certain Microorganisms, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 267-277, IAEA, Vienna, 1968.
67. M. H. Awan, D. Mohammad, and Q. A. Qadir, Modification of Qualities of Jute-Fibre: Effect of Percentage Graft on Breaking Load of Jute-Yarn, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 278-285, IAEA, Vienna, 1968.
68. L. S. Bonoan, The Status and Technology of Polymer-Containing Fibrous Materials in the Eastern Hemisphere: The Philippines, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 286-292, IAEA, Vienna, 1968.
69. U.-P. Wang, Factors Affecting the Impregnation of Bagasse and Other Far-Eastern Fibrous Materials, Proceedings of IAEA Study Group on Impregnated Fibrous Materials,

Bangkok, Thailand, November 20–24, 1967, pp. 35-44, IAEA, Vienna, 1968.
70. U.-P. Wang, The Status and Technology of Polymer-Containing Fibrous Materials in the Eastern Hemisphere: Taiwan, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 293-302, IAEA, Vienna, 1968.
71. M. L. Anong Nilubol and S. Greethong, Some Investigations on Radiation Polymerization in Thailand, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 303-304, IAEA, Vienna, 1968.
72. D. L. Stacey, Fibrous Material Resources in Asia and the Far East, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 315-325, IAEA, Vienna, 1968.
73. S. Dilli and J. L. Garnett, Radiation-Induced Reactions with Cellulose, *J. Appl. Polym. Sci.*, **11**: 839 (1967); *Aust. J. Chem.* **21**: 397 (1968).
74. J. G. Clouston, The Status and Technology of Polymer-Containing Fibrous Materials in the Eastern Hemisphere: Australia, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 217-230, IAEA, Vienna, 1968.
75. M. Gotoda, Emulsion Graft-Polymerization to Wood by Gamma Radiation, Proceedings of IAEA Study Group on Impregnated Fibrous Materials, Bangkok, Thailand, November 20–24, 1967, pp. 107-114, IAEA, Vienna, 1968.

Dosimetry, Tolerance, and Shelf-Life Extension Related to Disinfestation of Fruits and Vegetables by Gamma Irradiation

By E. K. Akamine, J. L. Brewbaker, I. Buddenhagen, K. Hilker, D. Kinch, J. Moy, E. Ross, H. Spielmann, and M. Upadhya

USAEC Report UH-235P5-3, Annual Report, June 1, 1966, to May 31, 1967

During the first 2 years of this contract, tolerance (optimum retention of nutritional and organoleptic qualities) to gamma radiation of papaya (Solo variety), mango (several varieties), and pineapple (Smooth Cayenne) was studied. Effective disinfestation doses of 25 and 33 krads for papaya and mango, respectively, were established by USDA workers. A significant shelf-life extension was evident with higher doses, which were still within tolerance limits.

In 1966–1967, research on the same three commodities was increased. Respiration studies on several fruits indicated an inverse relation between the degree of tolerance to radiation and the initial increase in respiration caused by radiation. Avocado, the least tolerant fruit, showed the greatest increase in respiration; papaya, the most tolerant fruit, showed the least increase—with soursop, mango, and yellow passion fruit between the two extremes.

Studies on pineapple indicate an autotoxicopectic mechanism that neutralizes the cytotoxic substances in the fruit during postirradiation (30 and 50 krads) storage of 8 days. Among postharvest pathogens, *Rhizopus* was found to be most resistant; cytoplasmic changes were observable in spores irradiated at lethal doses. Irradiation plus fumigation with 2-amino butane gave better disease control in papaya than either treatment alone. The incidence and severity of disease in mango were significantly reduced by doses above 240 krads.

A telephone survey conducted in two California cities found that there would be a 23% reduction in the present demand for papayas if irradiated papayas were introduced at this moment. However, many refused to consume irradiated foods because of a lack of information. The number of hard-core opponents seemed to be negligible.

An additional 26 varieties of Hawaiian avocados were investigated for radiation tolerance, bringing to 47 the number of known varieties that are intolerant to radiation. No significant organoleptic differences were noted between control and irradiated bananas, but no shelf-life extension was found, either. Lychees irradiated at 50 to 200 krads showed increasing amounts of total proteins and reducing sugars with increasing dose; there was a general increase in phenolic substances, which appears to be the result of radiation injury.

Equipment design studies showed that heating (or cooling), necessary with irradiation for disease control in most fruits, is done best by shower rather than immersion.

Poi, a steamed and mashed product prepared from taro root, is of potential economic significance as a low-allergen baby food. A certain amount of lactic acid fermentation is considered good, but too much limits the shelf life. Results of studies indicate that a refrigerated shelf life of several weeks would appear to be feasible for poi irradiated at 750 krads. Critical microbiological studies are needed to evaluate public-health hazards, however. (FEM)

Section

VI

Isotopes and Radiation Technology

Miscellaneous

Availability of Materials and Services

Cyclotron Corporation Makes a Variety of Accelerators

The Cyclotron Corporation of Berkeley, Calif., is marketing cyclotrons suitable not only for nuclear research but also for radioisotope production. The research unit is a 15-Mev negative-ion injector device which, when coupled with a tandem accelerator, provides a source of wide-energy-range protons for research aimed at clarification of the nature of nuclear forces. Duke University already has such a device, and Lawrence Radiation Laboratory is purchasing an advanced version that also has the capability of accelerating positive protons, deuterons, and helium ions suitable for charged-particle activation analysis and radiochemistry studies.

The company also manufactures cyclotrons for production of radioisotopes—one version suitable for hospital use, such as is to be used by the Argonne Cancer Research Hospital for research in cancer diagnosis, and a model for commercial production, as will be used by New England Nuclear Corporation. (PSB)

Radiation Machinery Corp. Irradiation Facility

A relative newcomer to the process radiation field, Radiation Machinery Corp. (RMC), Parsippany, N. J., has broken ground for a multipurpose irradiation facility, a $2-million plant in Hanover, N. J., designed for a 5-million-curie ^{60}Co irradiator, hot-cell facilities, and irradiator assembly lines.

The president of RMC is Milton Packin, a cofounder of Gourdine Systems Inc., and formerly with Curtiss-Wright and Isochem Inc. RMC will be organized into three divisions: Educational, Medical, and Processing. They now have one product on the market—the Gammator, a 400-curie ^{137}Cs irradiator selling for $3875 and intended for high-school laboratory use.

ORNL Stable-Isotope Inventory

Recent additions to the Oak Ridge National Laboratory (ORNL) enriched-stable-isotope saleable inventory include the following:

Isotope	Purity, %	Amount available, g
^{40}K	82.8	0.006
^{40}K	78.9	0.29
^{40}K	35.7	0.21
^{43}Ca	31.7	0.38
^{98}Mo	97.6	338.4
^{109}Ag	99.3	24.47
^{142}Nd	97.6	10.06
^{143}Nd	91.1	9.83
^{146}Nd	97.5	2.41
^{144}Sm	95.1	5.69
^{144}Sm	85.6	5.71
^{201}Hg	81.5	4.26

In addition to the regular inventory, ORNL maintains a rather large research materials collection; for further information regarding availability from this inventory, write Isotopes Sales Department, Oak Ridge National Laboratory, P. O. Box X, Bldg. 3037, Oak Ridge, Tenn. 37830. (PSB)

AERE Postgraduate Education Centre

The curriculum of the AERE Postgraduate Education Centre at Harwell (England) has included or will include the following courses:

For Science and Mathematics Teachers: Background information on current developments in some of the subjects investigated at Harwell, with an alternative section introducing the use of radioisotopes in schools in phys-

ics, chemistry, and biology. The aim is to evoke interest in recent applications rather than to provide material directly applicable to a school syllabus and should be of interest to teachers in Colleges of Education.

Medical Radioisotope Generators: Gives users and potential users of radioisotope generators practical experience with established and newly introduced systems.

Introduction to Radioisotopes: For those with preliminary training in a scientific field who need an introduction to the techniques of handling and measuring radioactive materials, mainly at the tracer level.

Radiological Protection: Gives users of radioactive substances and radiations in industry, research, or teaching a broad introduction to the principles and practices of radiological protection.

Australia Supplies Solid Radioactive Sources for Calibration Purposes

The Australian AEC is supplying solid sources of selected radioisotopes (Table 1) at certified disintegration rates for use in calibration of radiation counters and spectrometers. The sources are made in two forms: (1) 2π beta, gamma, and X-ray sources, and (2) 4π gamma and X-ray sources. The gamma sources are shown in Fig. 1. The diameter of the radioactive source material is normally 2 to 3 mm, and the source covers are 2.4 mg/cm^2 polyethylene film. The beta sources are similar in form except that their backing contains sufficient material to ensure saturation conditions for backscatter. Activities normally supplied are 3000 to 5000 photons/sec for gamma sources and 300 to 3000 counts/sec for beta sources. Other activities, to an upper limit of about 1×10^5 dis/sec, can be supplied upon request.

Table 1 Normally Available Radionuclides

Nuclide	Half-life	Characteristics of principal ray (approximate)		Price, A$
		Energy, kev	No. per disintegration, %	
Gamma emitters				
Americium-241	458 years	60	36.4	35
Bismuth-207	28 years	1060	76	
Cesium-137	30 years	662	86	30
Chromium-51	27.7 days	323	9.8	30
Cobalt-57	271 days	122	89	35
Cobalt-60	5.26 years	1170 1330	100 100	30
Iodine-131	8.08 days	360	79	
Manganese-54	313 days	840	100	35
Mercury-203	47 days	279	81.5	35
Niobium-95	35 days	760	99.8	
Sodium-22	2.62 years	1280	100	40
Yttrium-88	107 days	1840	99.5	
Zinc-65	245 days	1110	49	
Beta emitters				
*Chlorine-36	3×10^5 years			
Nickel-63	120 years			
Phosphorus-32	14.3 days			
Sulphur-35	87.2 days			
Strontium-90 + Yttrium-90	28 years			30
*Thallium-204	3.76 years			30

*A branch of 1.7% for ^{36}Cl and of 2.0% for ^{204}Tl decays by electron capture, leading to the emission of the characteristic X rays of the daughter.

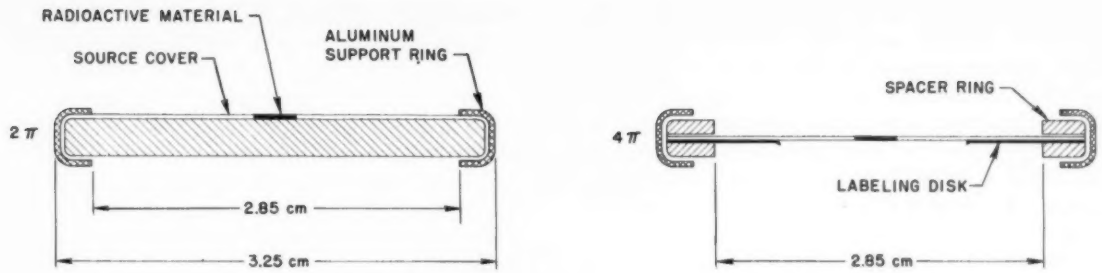


Fig. 1 Gamma sources. The radionuclide and an identification number are inscribed on the polyethylene support for the 2π source and on a polyethylene labeling disk for the 4π source.

Conferences

Packaging and Transportation Meeting Held at Gatlinburg, Tennessee*

The Second International Symposium on Packaging and Transportation of Radioactive Materials was held at the Gatlinburg Civic Auditorium, Gatlinburg, Tennessee, October 14–18, 1968, and over 400 people, 43 from 13 different foreign countries, attended. There were sessions on transportation regulations and experience in their implementation; transportation experience and problems; standards for container construction; fire and impact testing of containers; container research, development, testing, and analysis; and a panel discussion on cask model testing. A complete program was given earlier in *Isotopes and Radiation Technology*, 6(1): 120-126 (Fall 1968).

Proceedings[1] and six papers[2–7] not available at the time of the Proceedings' printing were presented to each attendee at the time of registration. The Proceedings (712 pages) are available for $3.00 from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U. S. Department of Commerce, Springfield, Virginia 22151. The six papers[2–7] not included are available from Her Majesty's Stationery Office, Cornwall House, Stamford St., London, England S.E. 1, at prices shown in the references.

Also distributed at the symposium were copies of the newly published (Oct. 4, 1968, *Federal Register*, Vol. 33, No. 194, Pt. II) Department of Transportation (DOT) regulations of shipment of radioactive materials.[8] This publication was especially important to those concerned with isotopes shipments because in January the Hazardous Materials Regulations Board published proposed amendments concerning a major revision to the regulations for the transportation of radioactive materials along with other general packaging modifications. During the 90 days the public was given for comment, numerous comments were filed, and these were studied by the department staff and discussed with the U. S. Atomic Energy Commission.

One of the most controversial items in the notice of proposed rule making involved the proposed changes in the regulations for the transportation of radioactive materials by air and bus. Restrictions on shipments of radioactive liquids and shipments of packages having significant external radiation levels had been proposed. After consideration of the comments received, and after evaluation of the impact of the proposal on the atomic energy industry, particularly with regard to the use of radiopharmaceuticals, those proposed restrictions have been deleted, and the present provisions for such shipments have been retained.

Numerous comments were also received regarding suggested changes to the Department's proposed labeling system for radioactive materials packages. The proposed system was in harmony with the regulations of the International Atomic Energy Agency (IAEA) and the proposed regulations of the United Nations. Certain parties in the United States felt that those international standards are not appropriate in all

*Sponsored by Union Carbide Corporation and the U. S. Atomic Energy Commission.

respects for U. S. usage and asked that the use of the labels be modified accordingly. However, the Department believes that the interests of international harmony in this area are overriding and has retained the IAEA-type labels and labeling criterions. The Department will pursue the item further with the IAEA to determine if changes could be made in the international standards which would reflect the total U. S. interests.

One of the highlights of the meeting was a field tour to ORNL where participants viewed the Oak Ridge Research Reactor; the old graphite reactor, now a national historic landmark; the High Radiation Level Examination Laboratory; the Isotope Packaging Area; and a display of radioactive materials shipping containers.

On display at the meeting were a demonstration fuel-element shipping cask (Fig. 1) designed and built from laminated uranium metal at the Paducah Gaseous Diffusion Plant, a National Lead Company cask for reactor fuels and waste, and several Tri-State Motor Transit Co. large tractor–trailer units for transporting radioactive materials (Fig. 2). After viewing this display and hearing the paper by Smith,[9] one can agree with Smith that the nuclear power industry will face many challenges in the shipment of irradiated fuels in the 1970's. Increased lengths of fuel assemblies coupled with increased specific power and exposures of fuel will result in multiplying the effects of increased length and greater required shielding thickness and, in addition, the increased total decay heat that must be dissipated from the cask. To further compound the problem, Smith foresees the quantities of irradiated fuels to be shipped to increase by a factor of 50 between 1970 and 1980.

(REG)

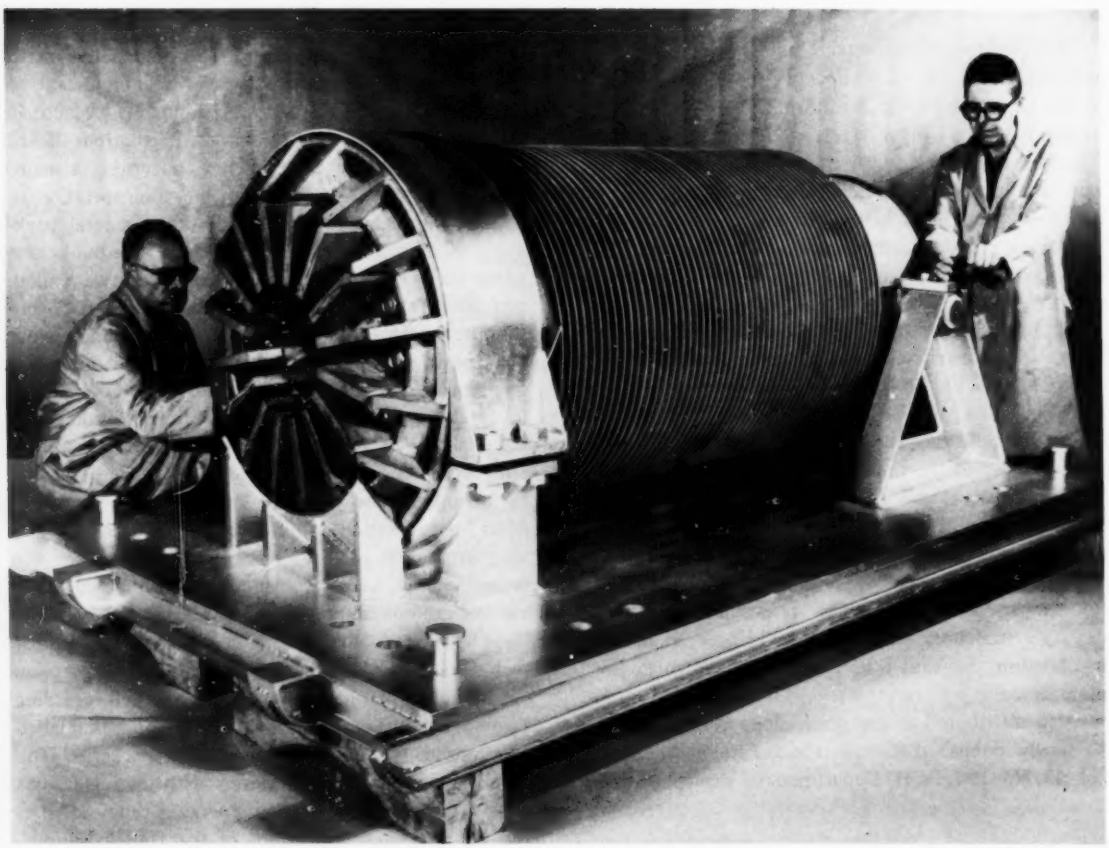
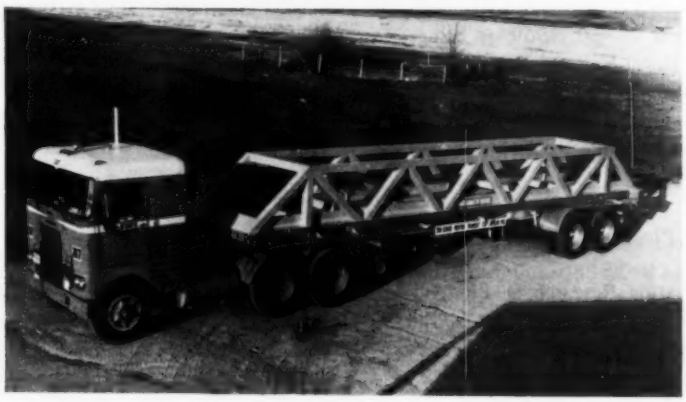


Fig. 1 Demonstration spent-fuel shipping cask made of laminated uranium.

(*a*)
Roll-top
trailer.



(*b*)
Bridge
trailer.

(*c*)
Placement of cask
on the bridge trailer.

Fig. 2 Tractor–trailer units for transporting radioactive materials.

References

1. Oak Ridge National Laboratory, Proceedings of the Second International Symposium on Packaging and Transportation of Radioactive Materials, Gatlinburg, Tennessee, October 14–18, 1968, USAEC Report CONF-681001, 1968.
2. F. E. Dixon and A. J. Brook, The Use of Thick Steel Wrapper Plates for Large Lead Filled Flasks, Which Could Obviate the Need for Special Thermal Shields, British Report AERE-R-5870, 1968 (9*s.* net).
3. F. E. Dixon and A. J. Davies, The Design and Testing of a Transport Capsule to Meet the I.A.E.A. Regulations, British Report AERE-M-2087, 1968 (3*s.* net).
4. F. E. Dixon, F. K. Olley, and L. R. Cohen, The Use of Massive Foamed Polystyrene in Radioactive Transport Packaging, British Report AERE-M-2086, 1968 (7*s.* net).
5. F. E. Dixon et al., The Design of a Ventilated Thermal and Mechanical Shield for a Heavy Lead Shielded Flask Which Contains a Heat Emitting Source, British Report AERE-R-5808, 1968 (10*s.* net).
6. F. E. Dixon and L. R. Cohen, A New Standard Series of Packagings for Loads Up to 40,000 Curies of Cobalt 60 or Equivalent, British Report AERE-R-5871, 1968 (3*s.* net).
7. F. E. Dixon, F. K. Olley, and L. R. Cohen, Type "A" Packaging for Liquids and Gases, British Report AERE-R-5701, 1968 (20*s.* 0*d.* net).
8. *Federal Register*, Vol. 33, No. 194, Pt. II, Department of Transportation, Hazardous Materials Regulations Board, Radioactive Materials and Other Miscellaneous Amendments, Oct. 4, 1968.
9. C. W. Smith, Shipment of Irradiated Fuel from Power Reactors in the 1970's, in USAEC Report CONF-681001, pp. 210-221, Oak Ridge National Laboratory, 1968.

Third Gatlinburg Isotopes Applications Conference Announced for April 1969

The Third Isotopes Applications Conference, scheduled for Gatlinburg, Tenn., April 27–30, 1969, is being jointly sponsored by Oak Ridge National Laboratory, Oak Ridge Associated Universities, and the U. S. Atomic Energy Commission. The $2\frac{1}{2}$-day meeting involves invited papers for two industrial sessions, a session on environmental applications, one on medical and biological applications, and a special half-day session on the preparation, analysis, and applications of ^{13}C. For further information, write: J. H. Gillette, P. O. Box X, Building 3047, Oak Ridge, Tenn. 37830.

Plastics Conference To Deal with Process Radiation

The College of Engineering Research Division of Washington State University will conduct its Sixth Pacific Northwest Plastics Conference jointly with the Office of Nuclear Energy Development, Department of Economic Development of the State of Washington, to discuss "Process Radiation in the Plastics Industry." The meeting will be held in Pullman on June 11–13, 1969, just preceding the American Nuclear Society Meeting in Seattle. For details contact Dr. R.A.V. Raff, Program Chairman, WSU, Pullman, Wash. 99163.

Ispra Nuclear Electronics Symposium Announced

The North Italy Section of the Institute of Electronics Engineers will sponsor an international symposium on nuclear electronics, at Ispra, Italy, on May 6–8, 1969. Subjects expected to be covered are: preamplifiers for nuclear detectors; amplifiers: shaping, d-c restoration, and base-line shift; problems of time resolution; pulse-height analyzers; time sorters; computers: on line and for data reduction in nuclear experiments; and statistics in nuclear electronics. For further information write Prof. Luciano Stanchi, C.C.R. Euratom, 21020, Ispra (Italy).

9th Japan Conference on Radioisotopes

The 9th Japan Conference on Radioisotopes is to be held in Tokyo May 13–15, 1969. It will be jointly sponsored by the Japan Industrial Forum, Inc., the Japan Radioisotope Association, Inc., and the Atomic Energy Society of Japan. Subjects for the symposium sessions include: X-ray fluorescence analysis using radioisotopes; fission tracks and their applications; applications of activable tracers; applications of radio-

isotopes to exploitation of natural resources; short-lived active species in radiation chemistry; radiation polymerization; new instruments for nuclear medicine; application of electronic computers in nuclear medicine; in vitro testing using radioisotopes; utilization of radioisotopes in plant-nutrition studies, e.g., plant metabolism, nutrient uptake, and chemical regulation (including herbicides); and new applications of radioisotopes in life-sciences research.

Further information can be obtained from Junichi Hayakawa, Director and Secretary General, Japan Industrial Forum, Inc., 1-13 1-chome, Shimbashi, Minato-ku, Tokyo.

General

Gamma Process Company Doubles Capacity of Irradiation Plant

Gamma Process Company has doubled the capacity of its Chicago (Morton Grove) irradiation plant by increasing the ^{60}Co radiation source strength from 100 thousand curies to 200 thousand curies. The doubling of the radiation source doubles the amount of products the plant can handle, and additional service is being provided by a fourth shift, added to permit around-the-clock operation 7 days a week. The expansion is in response to the higher demand for irradiated products.

Martin Marietta Bows Out of Isotope Generator Field

Martin Marietta Corp. has sold its nuclear activities to Teledyne, Inc., including government contracts for space isotopic generators, e.g., SNAP-19 and SNAP-29; its commercial line of isotope thermoelectric generators for terrestrial, water, and underseas uses; and related patents. The activities will be taken over by Isotopes, a Teledyne company, which will operate in Baltimore. J. Lawrence Kulp, Isotope's president, said that the acquisition brings together two largely complementary capabilities, nuclear physics and radiochemistry, plus materials technology and nuclear systems engineering. Isotopes will transfer its nuclear systems engineering work from Westwood, N. J., to Baltimore.

The company plans to expand the new division's line of radioisotope generators beyond the range of 1 to 100 watts, moving into both the lower power range and perhaps up to the kilowatt range. Development of Martin's Terrestrial Unattended Reactor Power System (TURPS) concept probably will be continued.

Mound: Builders of the Nuclear Age

In remarks at the 20th Anniversary Celebration of the Mound Laboratory, Miamisburg, Ohio, Oct. 18, 1968, Dr. Glenn T. Seaborg, Chairman, U. S. Atomic Energy Commission, summarized Mound's work in the field of nuclear energy. In the field of the use of radioactive isotopes, Mound (Monsanto) has extended its wartime work on polonium to the development of this isotope as a peaceful source of nuclear power. New compounds, including a series of rare-earth polonides, have been synthesized, and the methods developed have increased processing quantities by a thousandfold and are helping to bring down the cost of polonium.

Plutonium-238 metal and oxide have been prepared for use as fuel in SNAP generators, and processing techniques have been developed which have greatly increased the usefulness of ^{238}Pu as a radioisotopic fuel. Mound has also played a significant role in developing isotope-powered thrusters for low-power propulsion requirements in space, the DART (Decomposed Ammonia Radioisotope Thruster). The capsules for another isotope-powered thruster experiment, the POODLE, were also designed and fabricated.

Much of the work on the radioisotope heat source for use with the Brayton-cycle power conversion system will be done at Mound. This is a project to develop a ^{238}Pu fuel source for a space generator that would produce several kilowatts of electricity.

Mound is also developing other isotope-powered equipment for space programs, including an energy source for part of the life-support system for manned space flight. Radioisotopes will be used as an energy source for the waste-management and -recycling system, and Mound has fabricated ^{238}Pu heat sources for a prototype that has already been tested.

Mound is contributing to the development of an isotope-powered heater for a swimsuit (for divers in

very cold waters) by providing the ^{238}Pu source that heats water circulating through plastic tubes interwoven through the suit.

Aspects of two of the most important programs in the medical applications of the atom are being carried out at Mound, where work has been done on developing ^{238}Pu power sources for the cardiac pacemaker and the artificial heart.

Searle To Have Japanese Subsidiary

G. D. Searle & Co. will make and sell radiation instruments in Japan through a joint venture of Amersham/Searle [*Isotopes and Radiation Technology*, 6(2): 214 (Winter 1968–1969)] and Shimadzu Seisakusho, a leading manufacturer of scientific instruments and precision machinery in Kyoto. Searle will hold 49% of the equity in Shimadzu-Searle Instruments Co., which will operate under 10-year license agreements between the parent firms. Searle earlier set up a 50-50 joint venture, Marupi-Searle Co., to promote and market drugs produced in Japan under license by Dai Nippon Pharmaceutical Co., Marupi-Searle's other parent firm. (*Chemical and Engineering News*, p.19, Aug. 19, 1968.)

Swiss Radioisotope and Radiation Technique Center Established

A Swiss center for studying and applying radioisotope and radiation techniques was established recently in Schwerzenbach-Zürich by Inreseor—International Forschungsgesellschaft AG, a subsidiary of the Heverlein-Gruppe—in partnership with the Oerlikon-Bührle Holding AG. The Center will study radioisotopic techniques in nondestructive testing, gaging, and material tracking; radiation-induced polymerization, materials modification, and chemical synthesis; and large-scale irradiations for food preservation and medical-article sterilization, with packaging studies included. The 100-thousand-curie ^{60}Co source will also be available for commercial irradiations.

AEC Activities

John W. Landis Heads AEC's Committee on Isotopes

John W. Landis of Washington, D. C., formerly vice chairman of the Atomic Energy Commission's Advisory Committee on Isotopes and Radiation Development, has been appointed chairman by AEC Chairman Glenn T. Seaborg. Landis is Regional Vice President of Gulf General Atomic, Incorporated, and succeeds John L. Kuranz, President of Amersham/Searle and Senior Vice President of Nuclear-Chicago Corporation, who has resigned from the committee after 10 years of service.

Appointed as a committee member was Robert E. Kettner, formerly Assistant to the President of Consumers Power Company at Jackson, Mich., who is now organizing his own nuclear firm.

Radioisotope Licensing Procedures Revised

The AEC has revised its radioisotope licensing procedures to establish two new types of broad licenses under which certain licensees will have greater flexibility in their operations. The new Type B and Type C broad licenses will be similar to the current provisions for broad licenses, which will be designated Type A. The existing Type A licenses allow institutions with large-scale radioisotope programs to change the types of radioisotopes, their uses, and their users without license amendments. The new Type B and Type C broad licenses will extend this flexibility to users who have small to intermediate radioisotope programs. The revisions will not relax safety standards or lessen licensing requirements for training, experience, facilities, and equipment.

In addition to the new types of broad licenses, the revision to the AEC's Part 33 will expand the scope of the uses authorized in all broad licenses.

The proposed revisions of Part 33 were reported in *Isotopes and Radiation Technology*, 6(2): 217 (Winter 1968–1969).

Proposed Exemption from Licensing for Small Quantities of Radioisotopes

To bring the regulations up-to-date and better accommodate users, USAEC is proposing to exempt from licensing certain small quantities of radioisotopes

now used under general license and to increase the number of radioisotopes to which the exemption would apply.

In the existing Part 31, the Commission's regulation dealing with general licensing of by-product material, there is a schedule of kinds and quantities of radioisotopes that may be used under general license, i.e., without the filing of an application with the Commission. This schedule has not been revised since 1956, but since that time more radioisotopes have become available; new safety analyses have been made; potential users have become more familiar with the properties of radioactive materials; and those interested in using the radioisotopes would like to have larger quantities available. With the development of tracer methods and more sensitive instrumentation, these small amounts of radioisotopes have gained wider use. They are used increasingly as teaching aids, and their research applications are expanding. The proposed amendments are responsive to the comments and recommendations of the Commission's Advisory Committee on Isotopes and Radiation Development and the Commission's ad hoc Radioisotopes Licensing Review Panel.

The revisions would increase the number of radioisotopes listed from 65 to 171, the distinction between sealed and unsealed quantities would be dropped, and quantities of material would be modified. All but 10 of the new quantities are larger than those presently listed for generally licensed unsealed sources, but the quantities of these 10—^{131}I, ^{56}Mn, ^{204}Tl, ^{144}Ce, ^{60}Co, ^{154}Eu, ^{210}Po, ^{106}Ru, ^{89}Sr, and ^{90}Sr—have been somewhat decreased. The Commission has requested specific comments as to whether the reduction in quantities for these radioisotopes will affect established uses.

The license exemption would extend only to users of the radioisotopes. Producers or distributors would be required to have a specific license from the AEC. Such licenses would prohibit the use of the materials in any food, beverage, cosmetic, drug, or medicine, as well as their incorporation into any product intended for commercial distribution, and would require that each exempt quantity be separately packaged and have an attached label and accompanying brochure to provide radiation safety precautions and instructions. No more than 10 individually packaged exempt quantities could be placed in any outer package, the dose rate from the outer package should not exceed 0.5 mrem/hr, and not more than 10 quantities could be sold or transferred to an exempt person in any single transaction.

Other proposed amendments would specify that the materials are not intended for use in humans.

In Appendix C of Part 20, there is a schedule of small quantities of radioisotopes which may be disposed of by release to sewer systems or by burial in soil. Another proposed amendment would revise the quantities in Appendix C to conform to the quantities listed in the proposed exemption in Part 30, would add the isotope ^{241}Am, and would change certain other quantities listed in Appendix C.

These proposed amendments to Parts 20, 30, 31, 32, and 35 were published in the *Federal Register* on Aug. 10, 1968, 60 days were allowed for public comment, and the comments are now being studied by the AEC with an eye to possible revision of the proposal.

First Sale of Americium and Curium Isotopes

The USAEC is making available for sale to commercial and industrial organizations, for the first time, up to 10-mg quantities of two transplutonium isotopes, ^{243}Am and ^{242}Cm, priced at $100 per milligram. Also available is ^{252}Cf, a maximum of 1 μg to any one purchaser; this nuclide was previously available only on loan.

At a symposium on ^{252}Cf sponsored by the New York Metropolitan Section of the American Nuclear Society, AEC Chairman Glenn T. Seaborg emphasized that the applications of ^{252}Cf "...could have a far-reaching effect in improving our health, giving us higher quality products from our industrial complexes, and increasing our energy resources" and pointed out that the great variety of applications foreseen for this isotope make it a "bargain at almost any price." Small amounts of ^{252}Cf may someday do the job of a large and costly reactor or accelerator as a source of neutrons.

The largest single shipment of ^{252}Cf ever made—about 1 mg—was that of Sept. 30, 1968, from Oak Ridge to Savannah River. The first shipment to a user not within the AEC family of laboratories is now being made to the M. D. Anderson Hospital in Houston, Tex., as a loan for use in cancer research. The material is in the form of several needles, containing a total of about 230 μg of the isotope.

The transplutonium elements may be purchased from Isotopes Sales Department, Oak Ridge National Laboratory, P. O. Box X, Bldg. 3037, Oak Ridge, Tenn. 37830. Persons purchasing americium, curium, or californium must have a license issued either by the U. S. Atomic Energy Commission or by an Agreement

State, i.e., one to which the AEC has transferred, by formal agreement, certain regulatory authority over radioactive material.

Schedule of Plutonium Charges Established

The Atomic Energy Commission published in the *Federal Register* of Oct. 16, 1968, a schedule of charges for various isotopic assays of plutonium in the chemical form of plutonium nitrate:

Wt% ^{240}Pu in plutonium	Cost per gram of ^{239}Pu plus ^{241}Pu in plutonium, $
3	60
6	48
8	43
12	42
25	60
30	70

This schedule of charges is effective immediately, except that (1) no increase or decrease in charges will apply through June 30, 1969, to plutonium distributed earlier by lease before and (2) the charge of $43 per gram of ^{239}Pu plus ^{241}Pu will continue to apply through June 30, 1969, for plutonium of standard isotopic assays defined as plutonium containing 6 to 12% ^{240}Pu.

TRW Inc. To Develop Space Nuclear Power System

The AEC plans to negotiate a contract with TRW Inc., Redondo Beach, Calif., for design and development of a Radioisotope Thermoelectric Generator (RTG) for use on Navy "Transit" navigation satellites. The 20-watt generator will be fueled with ^{238}Pu. Development objectives for the generator are a 5-year operating life and a weight of less than 20 lb.

ORNL Retires 20-Year-Old Low-Intensity Testing Reactor

After a life of almost 20 years, Oak Ridge National Laboratory's Low-Intensity Testing Reactor (LITR) was shut down and retired from service Oct. 10, 1968. Though few reactors are older, it was technical obsolescence, rather than old age, which was the immediate cause of its demise. The LITR was originally built in 1948 as a hydraulic mock-up of the Materials Testing Reactor, which was subsequently constructed at the Atomic Energy Commission's National Reactor Testing Station in Idaho. The mock-up went through several developmental stages and, by 1953, under the name "Low-Intensity Testing Reactor," had a power level of 3000 kw(t). Until the construction of the Oak Ridge Research Reactor in 1958, the LITR was in many respects the most important nuclear reactor at the Oak Ridge National Laboratory. It was operated nearly 90% of the time for irradiation and testing programs for ORNL and other scientific establishments and was a major producer of radioisotopes.

(RHL and MG)

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